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VOL. I

HUMAN FACTORS DESIGN STANDARDS FOR THE FLEET BALLISTIC MISSILE WEAPON SYSTEM

VOLUME 1 DESIGN OF SYSTEMS

PUBLISHED BY DIRECTION OF DIRECTOR, SPECIAL PROJECTS

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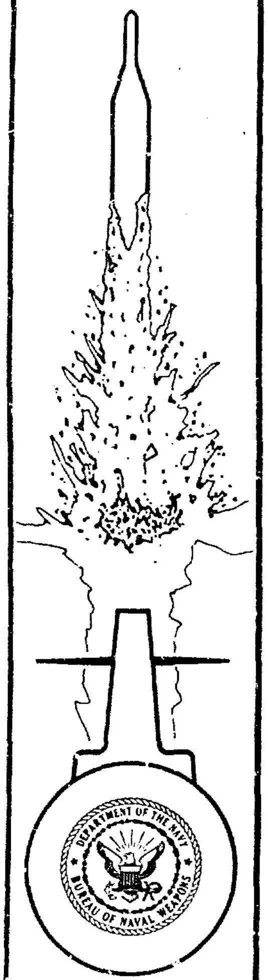

HUMAN FACTORS DESIGN STANDARDS FOR THE FLEET BALLISTIC MISSILE WEAPON SYSTEM

MAY 1963

VOLUME 1 DESIGN OF SYSTEMS

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HUMAN FACTORS DESIGN STANDARDS FOR THE FLEET BALLISTIC MISSILE WEAPON SYSTEM

1. OD 18413A is promulgated for the information and guidance of all military, government, and contractor agencies participating in the development of the Fleet Ballistic Missile Weapon System. The purpose of this publication is to provide human factor guidelines for the design of the FBM Weapon System and its components. It is published in two volumes: Volume 1, Design of Systems; Volume 2, Design of Equipment.

2. Consideration of the guidance and information provided in this document is mandatory in new designs for FBM Weapon System equipment and components scheduled for installation in SSB(N) 616 and later class submarines. Notice of errors, omissions, and corrections should be submitted to the Special Projects Office (Sp2012), Department of the Navy, Washington 25, D. C.

3. OD 18413A supersedes all previous issues of this publication which should be destroyed. Evaluations of Control-Display Components, included in previous issues, have been discontinued.

Levering Smith

LEVERING SMITH
Technical Director

PREFACE

The basic objective of this handbook is to provide special assistance to system and component engineers and human factors specialists in perfoming those portions of their engineering activities which may result in the specification or design of hardware to be operated and/or maintained aboard FBM submarines. The principles or guidelines in the handbook are based upon compilation of research findings and logical analysis and are expressed in terms which permit direct engineering application.

As a matter of convenience, the handbook is being published in two volumes. Volume 1, "Design of Systems," contains Sections 1 and 2 of the handbook and provides a basis for establishing and evaluating alternative system and subsystem concepts with respect to man-machine requirements, capabilities, and trade-offs. Volume 2, "Design of Equipment," contains Sections 3 and 4 of the handbook and presents information on which to base the selection, utilization, and design of equipment to enhance human operation and maintenance activities and thus achieve improved system performance and availability. The two volumes will generally be used at different states of system and subsystem definition.

Section 1 of this volume describes the stages in the weapon system development cycle and presents guidelines for the application of human factors at each stage. This section is useful in estimating the required extent of such efforts in a development program.

Section 2 of this volume contains human factors considerations and guidelines to be used in the development of system concepts, man-machine roles and functions, and subsystem requirements. It is useful during the early stages of system development, when decisions about the employment of men and machines are being made.

ACKNOWLEDGMENTS

This handbook could not have been prepared without the continued encouragement and support of Vice Admiral R.F. Raborn, Rear Admiral I. J. Galantin, Rear Admiral Levering Smith, Mr. J.B. Buescher, and especially Mr. Solomon Burg, of the Special Projects Office. Special thanks are due to Dr. Robert M. Thomson, Dr. Martin I. Kurke, Dr. Armand N. Chambers, Mr. Paul Preusser, and other past and present members of the staff of Dunlap and Associates, who contributed unstintingly of their time and effort in providing inputs to this volume.

Joseph G. Wohl, Editor

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SECTION 1 HUMAN FACTORS AND THE SYSTEM DEVELOPMENT CYCLE

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The application of human factors techniques and knowledge at critical stages in the development cycle of a weapon system can be accomplished most effectively if an appreciation is gained of the steps involved in this development process and of the ways in which human factors can be applied at each step. This brief section provides a general description of the major steps in the system development cycle, identifies the type of organization and technical personnel involved at each of these steps, and indicates the range of human factors activities which will be useful to them in their work. In this sense, it is useful primarily to system R&D planners in estimating the human factors effort required for a given system development.

This section is intended also as an introduction to Section 2, in which the system engineering process per se is outlined and man-machine trade-off considerations and techniques are described.

+This section is concerned with the technical phases in the development of the FBM System; therefore, the management aspects of the process (e. g. , the letting of contract, management structures such as the Special Projects Office, and management techniques such as PERT are not included in the description.

I. DESCRIPTION OF THE CYCLE

The development of a complex system proceeds roughly through the phases shown in Fig. 1-1, progressing from the general and abstract to the specific and concrete. For a system as complex as the FBM system, these steps, in general, will be followed for the over-all development of the system. However, there is considerable overlap and variation in the process for individual subsystems and equipments. Each design ordinarily is subject to several iterations before it is accepted. For example, at the present time, three classes of submarines, two generations of Fire Control and Launcher Subsystems, and a continuously evolving Navigation Subsystem have been designed, with future generations in the planning design or prototype stages. However, for any individual equipment (on the assumption that it completes the design cycle successfully) this cycle will provide a useful framework within which to discuss the application of human factors to the design of the FBM system.

Having listed the various phases of a weapon system development cycle (with some hints as to the role of human factors), we shall now examine in closer detail the engineering and analytical activities involved, their relationship to man-machine considerations, kinds of human factors that are relevant to each phase, and the degree of sensitivity of the end product to these factors.

Phase 1: Definition of the System Operational Requirements and Constraints

Before initiation of the design of a system such as the FBM, extensive planning and exploratory investigations are required to:

a. Establish operational requirements for the system, including analysis of the anticipated conditions under which the system might be operated.

b. Identify technologies potentially capable of bringing the system into existence; for example, the availability and suitability of inertial guidance techniques and the use of solid vs. liquid propellant rocket motors.

c. Determine alternative system concepts applicable to the fulfillment of these requirements; for example, the use of moving launch platforms (i.e., submarines) vs. stationary undersea platforms.

The establishment of over-all weapon system requirements is made by the Office of the Chief of Naval Operations (CNO) and is based in part on the presumed

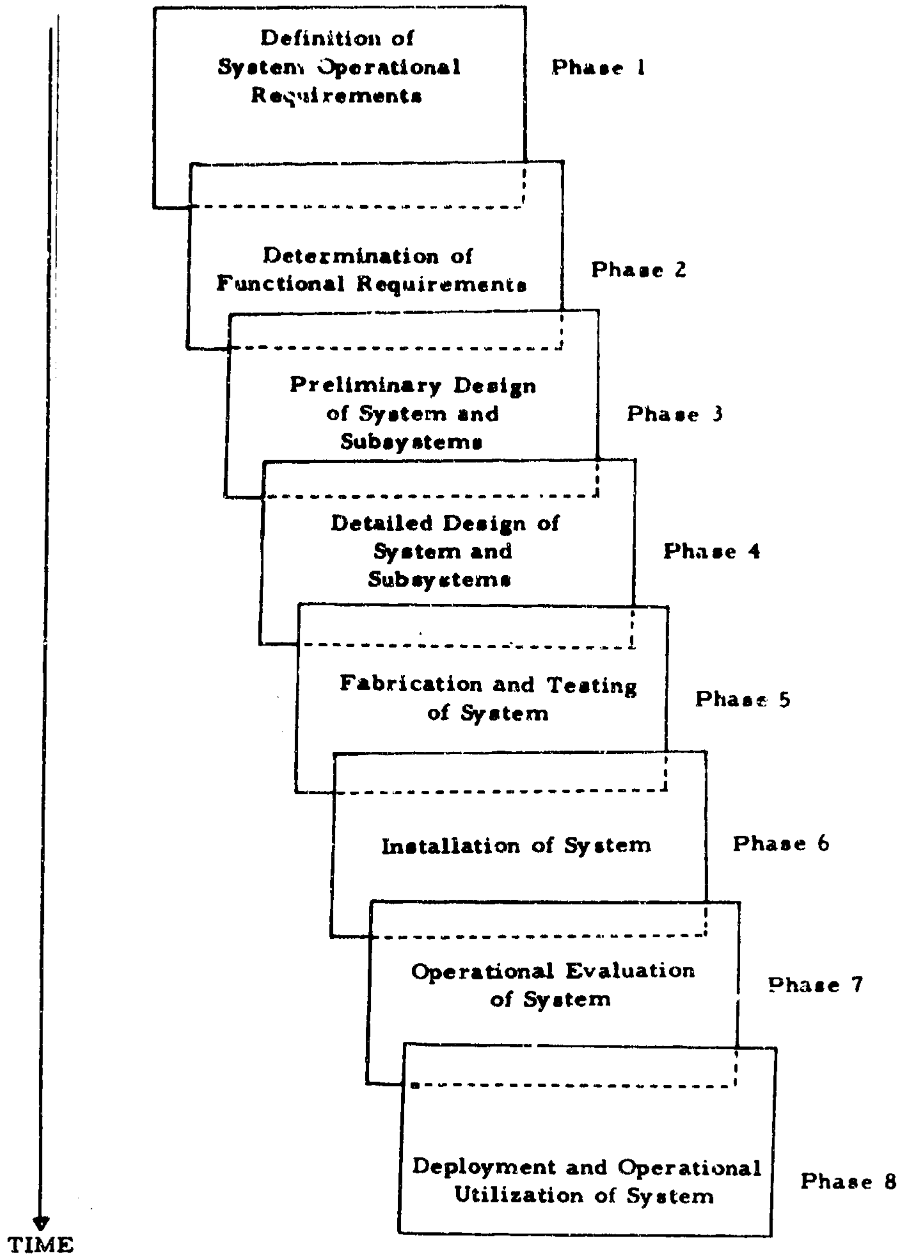

Fig. 1-1. Phases in development of a system

enemy capabilities at the time the system could be expected to be operational. This step ordinarily will be dependent on analyses performed by military agencies, research organizations, and industry for the provision of state-of-the-art and trade-off information which may result in modification of the requirements specified for the system. It is at this stage that critical decisions are made which have far-reaching effects upon such diverse items as performance, reliability, maintainability, personnel and training requirements, procurement costs, and spare parts costs. Early gross trade-off studies should be made at this level.

Human factors has had limited but important application at this early stage of FBM development. As an example, the question arose of the psychological and physiological effects of prolonged undersea patrols. This question, central to the development of the system, had to be answered before a final system concept could be developed. The atomic submarine, Nautilus, was used as a test bed for this purpose, making several cruises with prolonged subsurface operations and providing much useful data in the way of atmospheric control requirements and other aspects of submarine habitability. Thus, an important set of human factors constraints and requirements was established early in the development cycle.

Phase 2: Determination of Functional Requirements

Once decisions have been reached about the system operational requirements, the results are documented in the form of a Specific Operational Requirement (SOR), which is prepared by CNO and transmitted to the materiel bureaus for action. In response to this document, the lead bureau (BuWeps in this instance) must prepare a Technical Development Plan (TDP) which summarizes the functions which must be performed to satisfy these requirements and the conditions under which and tolerances within which the functions are to be performed. In addition, this TDP outlines the gross techniques and equipment concepts which will be used to fulfill these functional requirements. Preparation of the TDP for the FBM system has been a direct responsibility of the Special Projects Office of BuWeps. Typically, the TDP is based upon a functional requirements and feasibility study, or, more often than not, parallel studies performed by Navy, industry, university, and private research groups reporting to the Special Projects Office. These studies involve:

a. Detailed consideration of techniques and technologies which can meet the requirements (for example, the use of an inertial guidance system to provide the precise position information required for navigation over long periods of submerged operation, the selection of solid propellant fuels for the missile to reduce launch preparation time, etc.).

b. Specification of the time, accuracy, and reliability with which each function will have to be performed in order to meet the operational requirements of the system (for example, the missiles must be designed so they can be launched in "x " minutes, and the circular error probability for the missiles must be "y " yards, etc.).

c. Analysis of the conditions under which the system is expected to be operated to determine any constraints or special requirements that this might impose on the design (for example, the implications on the design of the missile of launching from a submerged position, the effects of sea state, the potential capabilities of the enemy to detect the submarine, etc.).

d. Development of mission profiles, including the hypothetical operation of the system throughout its mission in order to determine more precisely the design requirements and support requirements for the system.

e. Estimation of the development time and probable effectiveness of the system at the end of that time.

The types of personnel involved in these studies are usually conceptually oriented and include physicists, mathematicians, and systems engineers. During this critical phase of TDP development, the functional capabilities of the human being as well as the hardware and state-of-the-art capabilities must be taken into account, and man-machine (or manual-automatic) decisions must be made. Some cost trade-offs between man and machine are possible at this level, the results of which can help direct the assignment and distribution of functions among personnel and equipment.

The development of functional requirements and system concepts thus involves the performance of feasibility and trade-off studies to determine the most effective approach to use within the constraints imposed on the system. The results of these analyses and the approach that was to be followed in the development of the FBM system are stated in the Technical Development Plan for the FBM Weapon System.

Based on his knowledge of the capabilities and limitations of human behavior, the human factors specialist can contribute at this point to decisions about whether or not to use personnel to perform specific functions. At the command level, he is primarily concerned with decision-making requirements; for example, the complexities and unpredictability of the situation under which the system must operate obviously will require human judgment. At levels more

directly related to the hardware, he must consider such factors as the degree of automation of a particular subsystem or equipment. For example, the rapid firing rate required of the Mark 84 Fire Control System meant that an automatic firing mode would have to be provided because of man's inability both to process the amount of information that would be required of him and to respond within the time available. In other situations, such as checkout of the subsystems and equipments, a more manual mode of operation was both possible, because of the less stringent time limitations, and desirable in the interest of designing more reliable and flexible test equipment. The human factors effort during this phase thus represents an important contribution to the formulation of operational and maintenance concepts for the system.

Along with the development of the system concept, tentative planning for the selection of suitable types and number of personnel to man the system may also be done.

Phase 3: Preliminary Design

The FBM Technical Development Plan, as promulgated, incorporates the most feasible concepts and techniques for implementation of the functions. Thus, it is important that systems engineers and human factors specialists cooperate closely in this phase. The latter group typically provides such inputs as: (1) translation of subsystem requirements into specific personnel requirements for command, operation, maintenance, and support; (2) determination of general information and control capabilities required by the personnel; and (3) preliminary development and evaluation of alternative procedures which the personnel will use to perform their functions.

Phase 4: Detailed Design

After the specifications for the system or subsystem have been evaluated and approved, the individual equipment and component design phase is initiated. At this stage, the electronic and mechanical design details of each equipment are undertaken if -- as is often the case -- available equipment will not meet the requirements of the system. This involves: (1) preparation of electrical and mechanical design specifications for the equipment; (2) consideration of the interfaces between equipments and between equipment and personnel (in the form of controls and displays); (3) selection (or design, where required) of components which are required for the production of the equipment; and (4) development of operating and maintenance procedures.

These activities are typically the responsibility of contractor engineering personnel. At this point, man-machine considerations become quite specific and directly oriented towards hardware requirements:

a. Selection (or design, where required) of control and display components which meet human factors criteria for the conditions under which the equipment is expected to be operated.

b. Design and location of control and display panels and consoles, including the translation of information and control requirements into hardware requirements and the location and operation of the control and display hardware on these panels and consoles.

c. Electronic and mechanical design as it relates to test procedures and test equipment, location of test points, provisions for monitoring the status of the equipment, and the other considerations related to the maintenance of the equipment.

d. Determination of the compatibility of the equipment design with the operational and maintenance concepts that have been established for the system.

e. Detailed development of operational and maintenance procedures for the various modes and conditions of operation and the translation of these procedures into requirements for technical manuals and job aids.

f. Consideration of the design of operational equipment to permit its use as an effective medium for on-the-job training and maintenance of proficiency of FBM crews. +

Often, alternative techniques are compared and evaluated or individual portions of the equipment are mocked up and tested. For example, a Fire Control

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+ Although beyond the scope of this volume, as defined by SPO, technical management and engineering personnel must also be alert to potential problems related to requirements for manning, selection, training, motivation and morale, physiological habitability, logistic support, and information feedback.

Console simulator was fabricated for the Mark 84 Fire Control Subsystem to determine experimentally the ability of the operator to perform with various levels of automaticity.

At the same time the equipment or component specifications are being prepared, the requirements for training of personnel and the design of simulation and training equipment must also be developed.

Phase 5: Fabrication and Testing

When the detailed circuitry has been designed and provisions for packaging and interconnection of the equipment have been completed, the first prototype of the system is fabricated.+ Once this step has been completed, the test engineer interconnects the equipments of the system or subsystem and checks out their operability. At this time an examination of the system should be made from both design and operability standpoints to insure that no significant human factors problems exist or, if they do, to provide design or procedural recommendations for their elimination.

Phase 6: Installation of System

After the subsystems and equipments have been tested and approved, they are installed in the submarine and tested again, this time as an integrated system and under conditions approximating the operational and environmental conditions for which they have been designed. For the FBM system, this evaluation has ranged from interface circuitry testing of the subsystems through launching of missile test vehicles to launching of operational missiles.

Human factors continues as an important concern during this phase in the interests of determining any design, procedure, or training problems that may be disclosed only under these test conditions.

Phase 7: Operational Evaluation of the System

Once the system has been installed and determined to be operational, the next problem is that of determining whether it meets the established operational

+Under typical accelerated development schedules for FBM equipment, this step is often merged with the following two steps, because the first equipment fabricated often becomes the first operational equipment. This is important to recognize, since it emphasizes the need to include human factors considerations in the design of "engineering model" equipment.

requirements. At this time, the system is turned over to the user agency to perform this evaluation, usually with the support of contractor personnel. Information pertaining to man-machine effectiveness in the system should be made available during this evaluation period, to be used both for the correction of deficiencies in the existing equipment or procedures and for providing guidance in the development of later models or future systems.

Phase 8: System Deployment and Operational Utilization

When the entire system has been determined to meet operational requirements, it is deployed by the user agency to perform the functions for which it has been designed. Monitoring of operational human factors problems must continue during early system deployment, since utilization of the system under the conditions for which it has been designed remains as a final source of evaluation information. Solutions to such problems as are generated at this time not only provide answers to the problem at hand, but also provide a basis for the design of future equipment and systems. Information of this type for the FBM system has been obtained from the responses to human factors questionnaires filled out by the crews while on patrol as well as from observations by design personnel.

After a system has been operational for some time, it is almost inevitable that modifications of both a minor (SPALT) and major (model change) nature will be required. This may be the result of changes in operational requirements, unsatisfactory performance of the equipment, or advances in hardware state of the art. Man-machine considerations play an important role in establishing human engineering requirements for model changes and in determining the effects of SPALTs on operation and maintenance of the system.

In the FBM system, an extensive network of information feedback has been established to insure that operational experience from this program is available to management, personnel, training, design, and logistics activities, both to refine the present utilization of resources and to influence the early phases of follow-on programs.

II. GUIDELINES

The preceding discussion has identified the role of human factors in each phase of the FBM system development cycle. This information is conveniently summarized in Table 1-1 in the form of brief management guidelines for application of human factors throughout the cycle.

It is important to note that in proceeding through the cycle there is a progressive narrowing and limiting of design alternatives open to the engineer. This fact serves to underscore the importance of early consideration of human factors in each development stage.

Table 1-1
Guidelines for Application of Human Factors in System Development Cycle

Phases in System Development Cycle	End Product	Participating Agencies	System Engineering Activities	Relevant Human Factors Activities
1. Definition of system operational requirements	Specific Operational Requirement (SOR)	CNO	Mission requirements determination and analysis; identification of operating, weight, space, and other constraints	. Establishment of personnel implications and constraints (e.g., number, type, re-enlistment rate, training capabilities, operating environment)
2. Determination of functional requirements	Technical Development Plan (TDP)	Materiel Bureaus	Performance of gross trade-off studies; definition of system and subsystem types, hardware techniques and performance, reliability, and maintainability goals; determination of information transfer requirements throughout the system; establishment of operational, maintenance, and support concepts; development of system evaluation requirements	. Contribution to operational and maintenance concepts and maintainability goals . Participation in gross trade-off studies . Gross assignment of subsystem functions to personnel and equipment . Gross division of duties among personnel . Determination of implications for manning and training . Determination of implications for system evaluation
3. Preliminary Design of System and Subsystems	System and subsystem specifications	Materiel Bureaus and their contractors	Evaluation of alternative design concepts with respect to preceding step (e.g., analog vs. digital, mechanical vs. electrical); determination of installation requirements; performance of detailed trade-off studies; preparation of system and subsystem specifications	. Analysis of information transfer requirements throughout the system . Detailed assignment of subsystem functions to personnel and equipment for each alternative design concept . Translation of information transfer requirements into display, control, and processing requirements for each alternative design concept . Evaluation of each with respect to human factors (e.g., implications for number and types of personnel, training, job aids, man-machine interface design, data processing requirements, etc.) . General location of operator and maintenance stations . General design of functional procedures . Preparation of man-machine portions of subsystem specifications

Table 1-1 (cont'd)

Phases in System Development Cycle	End Product	Participating Agencies	System Engineering Activities	Relevant Human Factors Activities
4. Detailed Design of System and Subsystem	Equipment and component design specifications	BuWeps BuShips BuPers BuSandA Contractors	Reliability-maintainability analysis and prediction; determination of system and subsystem test and checkout requirements; logistic support analysis; generation of system evaluation plans, and of performance, reliability and maintainability reporting requirements and procedures; establishment of quality assurance and equipment modification (SPALT) programs; definition of personnel and training requirements; establishment of documentation (i. e., technical manual) requirements	. Translation of control and display requirements into hardware requirements . Specification of location and environment for operator stations . Selection and design, where required, of control and display components . Design of operator panels, consoles, and workspaces . Selection and location of communication equipment . Specification of operating and maintenance procedures for normal and non-normal modes of operation . Participation in system evaluation planning . Personnel manning and training requirements determination
5. Fabrication and testing of system	System prototype (or first model) and technical manuals	Materiel Bureaus, Contractors and subcontractors, BuPers	Continuing review of quality assurance program results and of early performance, reliability, and maintainability reports; definition of spare parts procurement, inventory, and transportation requirements; initiation and/or approval of minor modifications (SPALTS)	. Evaluation of prototype system from human factors standpoint . Recommendations of modifications to designs or procedures for operation and maintenance . Establishment of training courses . Familiarization of personnel with system
6. Installation and initial (dockside) operation of system	Completed system, ready for sea trials	Shipyards, materiel bureaus, contractors	Analysis of installation problems and reports; initiation and/or approval of minor modifications (SPALTS)	. Review of installation reports from human factors standpoint; recommendations of minor design changes . Training of personnel
7. Operational Evaluation of System	Test and evaluation reports	Materiel bureaus, OPTEV FOR, fleet, contractors	Analysis of individual test and evaluation reports+; initiation and/or approval of minor modifications (SPALTS); continuing review of system performance, reliability, and maintainability	. Review of test and evaluation reports from human factors standpoint + . Recommendations of design or procedural modifications . Determination of training adequacy and recommendation of changes
8. Deployment and Operational Utilization++	Operational deficiency reports	Fleet	Analysis of operational deficiencies; initiation and/or approval of minor modifications (SPALTS); continuing review of system performance, reliability, and maintainability	. Review of operational deficiency reports from human factors standpoint . Interviews with operating and maintenance personnel to obtain additional data . Recommendation of design or procedural modifications

+First-hand observation is extremely desirable if appropriate arrangements can be made.

++By this phase of the cycle, accumulated modification (SPAL) requirements, technological, or state-of-the-art improvements, and changes in operational or functional requirements may warrant a major design change (e. g., model change), in which case the cycle is repeated, starting with Phase 3.

SECTION 2 HUMAN FACTORS IN SYSTEMS ENGINEERING

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CONTENTS OF SECTION

This section develops and presents human factors considerations to be applied early in the design of the system when functional requirements are being analyzed, system concepts are being formulated, and functions are being assigned to man and machine. + It is intended for the military analyst, scientist, or systems engineer who -- whether consciously or not -- makes decisions about where man is to be utilized in the system and what functions he should be assigned.

For the systems engineer, it is useful in establishing a frame of reference in which to decide upon appropriate roles for man and machine and in determining how man-machine functions should be implemented. Further, it will aid in determining the location of personnel, the general nature of the duties and tasks to be performed by each, their information and control requirements, and estimations of the workload that will be imposed on each of the personnel. The end product of applying the information in this section is a set of man-machine interface requirements which can then be transformed into specific hardware requirements for displays, controls, panels, workspaces, etc.

Part I of Section 2 contains an intensive discussion of the various kinds of factors which influence man-machine integration; these include mission, system, use, and man-machine factors. The latter group is expanded upon in some detail with a discussion of human task trends in Naval weapon systems, definitions of fundamental man-machine tasks and the elements of which they are composed, a discussion of the nature of the man-machine interface, and, finally, a summary of relative capabilities and limitations of men and machines.

Part II, Man-Machine Integration, is divided into four major discussion areas. The first is a brief description of various system models as aids to task assignment in which different techniques of describing man-machine system operation are presented. One of these techniques, the Operational Sequence Diagram, is then described in detail. The differences between operational and maintenance interfaces between man and machine are also described, and the utility of each technique with respect to these interfaces is discussed.

+The term "system" is used here in a generic sense to refer to: (a) the entire FBM system; (b) subsystems within this complex; or (c) individual equipments, depending on the particular level of design to be discussed.

The second major area is entitled, "Man-Machine Task Assignment Guidelines." In this section specific guidelines for assignment of functions to man and to machine are presented and specific human requirements for sensing, processing, and actuating are identified.

The third area is that of evaluating task assignments to man vs. machine. Once a trial assignment has been made (and all assignments must be considered as such since the process is an iterative one during early stages of weapon system planning and design), it must be evaluated with respect to a number of system-oriented criteria. These criteria are listed and discussed, together with evaluation schemes. The fourth area deals with the end products of the systems engineering process insofar as human factors are concerned, namely, specification of man-machine interface requirements. The purpose of this final discussion in Volume 1 is to define the nature of the man-machine interface and to direct the reader towards the appropriate application of Volume 2, Design of Equipment.

I. FACTORS INFLUENCING MAN-MACHINE INTEGRATION

To gain a perspective on the role of human factors in systems engineering, it is important to understand the system engineering process itself. It may be conceived as a dynamic sequential decision process with limited reversibility, subject to several sets of constraints. Consideration of the realities of technical R&D requires further that the system engineering process be viewed as an heuristic process in which several alternative conceptions may be developed and carried along simultaneously, some or all may be altered or eliminated as a function of the constraints imposed at various development stages, and new conceptions may be developed. As the cycle proceeds and successive commitments are made to selected lines of development, the commitments themselves serve as a new set of constraints on later decisions. Often, certain constraints or new technological, military, political, or economic considerations may require that an entire line of development be dropped and the system be reconceived from an earlier step in the cycle.

Thus, in the final analysis, a weapon system is not really "developed" in the strict planning sense; rather, it is "grown" in the highest sense of the word. What we are saying, in effect, is that good system concepts may be selected and the conditions for their growth and maturation may be optimized in a properly planned and executed system development program. The end product of such a program is always a man-machine system in which man and machine perform complementary (and often supplementary, i. e., backup) functions. +

If the functions, operations, and actions defined for a given system could be assigned to man or machine on the basis of relative capabilities alone, the assignment task would not be very difficult. The significant decision problems arise out of the necessity to develop hardware and software for a specific system, to be used in a specific context, anticipating a range of variation in both system design and use. For example, although a general-purpose computer is both

+It is important to recognize that both man and machine are almost completely "programmed" in their performance by virtue of wiring (fixed equipment program), tape, card or drum storage (flexible equipment program), written procedures (fixed human program), training (flexible human program), and experience (flexible human program). We say "almost completely" because of the ever-present possibility of random behavior, as in equipment failure and human error.

feasible and economical for certain applications, its use for FBM navigation and/ or fire control may be unthinkable due to special requirements (e.g., reliability, independence) or constraints (e. g. , space).

These decisions normally are made during the initial or preliminary design stages of system development. It is important to note that they may not be "conscious" decisions per se, i.e., they may be constrained as a result of allied decisions in other areas, such as a decision to decentralize all digital data processing capability. Thus, as a continuing outgrowth of increasing concept and design specificity throughout weapon system development, the allowable degrees of freedom in both hardware and software concepts and in design become ever smaller. Toward the end of the development cycle, there are only minor variations allowed on a single design theme; and the final selection among these variations can be made on the basis of dollars, time, or whether the manufacturer is located in a depressed area. The point here is that effective planning requires that decision consequences be recognized early enough to change the course of design.

A final point deserving of introductory emphasis is that because functional requirements and constraints begin to be dictated (if not overtly recognized) early in the planning game, weapon system planners must become aware of the potential consequences of their decisions with respect to men, machines, and programming requirements.

A system development thus proceeds from a desired mission through the establishment of basic system functions required to perform the mission to the assignment of these functions to men, software (programming), and hardware (equipment). This process is strongly influenced by three sets of factors which we have labelled "system-determined factors," "use-determined factors," and "man-machine, or human, factors." The entire process is summarized in Fig. 2-1, which indicates the sequential and iterative nature of the process and identifies the factors which must be considered.

Man-machine factors cannot be discussed in isolation from the weapon system planning and development process, since they are deeply imbedded therein. Thus, is is of primary importance to understand the process itself. To this end, a series of tables (2-1 through 2-5) has been constructed to help identify and define the various factors and their multiple interactions. We shall progress through the tables in the direction of increasing system specificity, representing the planning and preliminary design portion of the weapon system development cycle. Each table will be discussed in detail, and examples will be given where appropriate.

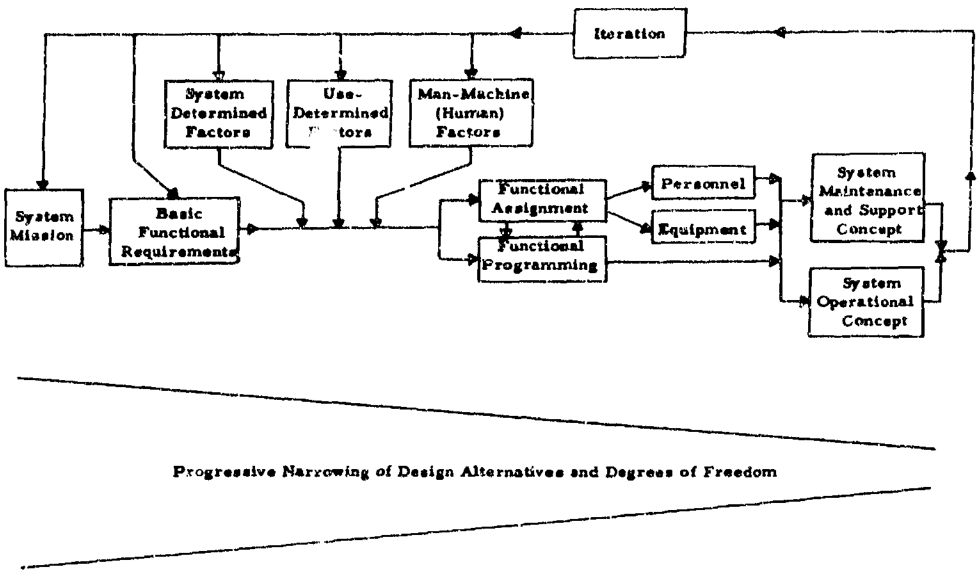

Fig. 2-1. Factors in Weapon System Development

1 <u>Mission-Determined Factors</u> (Table 2-1)

1.1 <u>Mission Types</u>

The very nature of the mission itself will immediately impose general constraints on system design and will thus influence man-machine function assignment. A given mission type (examples of which are listed in Table 2-1) will delimit the range and scope of system types from which a final selection can be made and similarly will determine the functions, performance requirements, and subsystem types. Within the present Navy context, the FBM mission (a combined one of deterrence and, failing that, strategic warhead delivery) dictates the employment of a surface-ship- and/or submarine-launched missile, with the latter system type preferred for its survivability and difficulty of detection. The functional phases of target-to-weapon assignment, navigation, weapon arming, and launching are also predetermined by the mission type with resulting direct influence upon man-machine assignments. Certain system performance requirements can also be established at this point based upon trade-off studies (e.g., warhead yield vs. missile guidance accuracy vs. submarine navigation accuracy vs. error in knowledge of critical target position.

Table 2-1
Examples of Mission-Determined Factors

Mission Types	Functional Phases: ASW Mission	Functional Phases: Airborne Weapon Delivery Mission	Performance Requirements
Deterrence	Proceed to Datum	Target Assignment	Speed
Reconnaissance	Navigate	Pre-Flight	Altitude
Shore Bombardment	Search	Take-off	Depth
ASW	Localize	Climb	Maneuverability
Harbor Defense	Classify	Patrol	Accuracy
Tactical Warhead Delivery	Track	Navigate	Weapon Yield
Strategic Warhead Delivery	Attack	Delivery	Turn-Around Time
Close-support	Post-Attack	Rendezvous	Response Time
Logistic Delivery	Assessment	Return-to-Base	Operational Readiness
Show-of-Strength		Land	System and Subsystem Availability
Communications		Post-Ops Analysis	MTBF (minimum)
Command/Control			Down Time (maximum)
Other			Detection Range
			Channel Capacity
			Memory Storage
			Data Rate
			Other

Weapon System Development Cycle
(Direction of Increasing Specificity)

1.2 Functional Phases

Each functional phase of a given mission type, together with other factors, will help establish the system performance requirements and system and subsystem types in a manner similar to that first described.

1.3 Performance Requirements

The partial listing in Table 2-1 is sufficient to indicate the scope of possible effects upon the assignment decision. For example, if count-down time is an appropriate and critical function for the FBM system, and if enemy missile characteristics and/or political considerations dictate that count-down time should not exceed 15 minutes, then critical missile checkout and readiness operations will have to be compressed in time such that there will be an over-riding need to automate some of the more time-consuming operations.

As another example, the high availability requirement of the FBM Navigation Subsystem may be met by increasing redundancy reliability, or

maintainability. This is easily seen by studying the availability function for redundant equipments.[+]

$$A_n = \left[1 - (1 - A)^n\right] = \left[1 - \left(\frac{T_d}{T_f + T_d}\right)^n\right]$$

where

A_n = redundant availability, or probability that at least one out of n equipments will be operable when needed

T_f = mean time to failure

T_d = mean down time

n = number of equipments (i. e., redundancy)

Either increasing n (redundancy) or T_f (reliability) or reducing T_d obviously will result in increasing availability, although increasing redundancy or reliability is generally more difficult and costly. Thus, in order to meet the Navigation Subsystem availability requirement, there has been a pressure to reduce down time by automating certain checkout and fault isolation functions in addition to the parallel effort to provide redundancy (e. g., 3 SINS, 2 NAVDACS) and improve reliability. It is also conceivable that in some cases system accuracy may be affected adversely by human intervention and that, as a result, certain critical procedures must be carried out automatically.

Finally, the need for rapid firing of the missiles requires a rate of information processing beyond human capabilities, thus dictating an automatic normal launch sequence.

2 System-Determined Factors (Table 2-2)

2.1 System Type

The very nature of a weapon system dictates many gross allocation limits. For example, while an FBM submarine is under way, the performance of checkout and maintenance of a Polaris missile is limited by the relative inaccessibility

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[+] This formulation implicitly assumes that each equipment has a repairman assigned to it full time. For a more detailed discussion, see this volume, page 27, and Volume 2, page 220 et. seq.

Table 2-2
Examples of System-Determined Factors

System Type	Subsystem Type	Subsystem Design Concepts	Design Constraints
Manned Aircraft	Weapon Carrier	Analog	Cost
FBM Submarine	Sensing	Digital	Weight
Helicopter	Data Processing	Mechanical	Volume
SAM	Navigation	Electrical	Personnel
Orbital Vehicle	Fire Control	Hydraulic	Safety
Data System	Launch	Pneumatic	State of the Art
	Guidance	Modular Design	
	Flight Control	Redundant Elements	
	Fueling	Built-in Checkout Features	
	Propulsion	Design to Simplify Operation	
	Payload or Weapon	Design to Facilitate Maintenance	

→ Weapon System Development Cycle (Direction of Increasing Specificity) →

of the launch tubes, requiring that critical subsystems such as guidance and flight control be monitored continuously and automatically.

Since any of the sixteen missiles can be launched at different targets, simple Go/No-Go checks on guidance accuracy often result in the less accurate missiles being down, whereas quantitative information concerning resulting CEP can permit re-targetting such that less accurate missiles may be assigned to nearer targets. (Note that in this instance a <u>less</u> automatic approach may result in <u>increased</u> system capability.)

2.2 Subsystem Type

Each subsystem type carries with it specific function allocation requirements, depending again on conditions of use. Guidance and navigation subsystems typically require careful alignment and accuracy checks in addition to straightforward "operating" checks. In contrast, there is no possible way to check out

the propulsion system of the solid-fuel missile. Flight control checks may be either operability-type (e. g. , hard-over jetavators in response to input signal) or response-determining type (e.g. , dynamic analysis), depending upon purpose of checkout and/or level of maintenance.

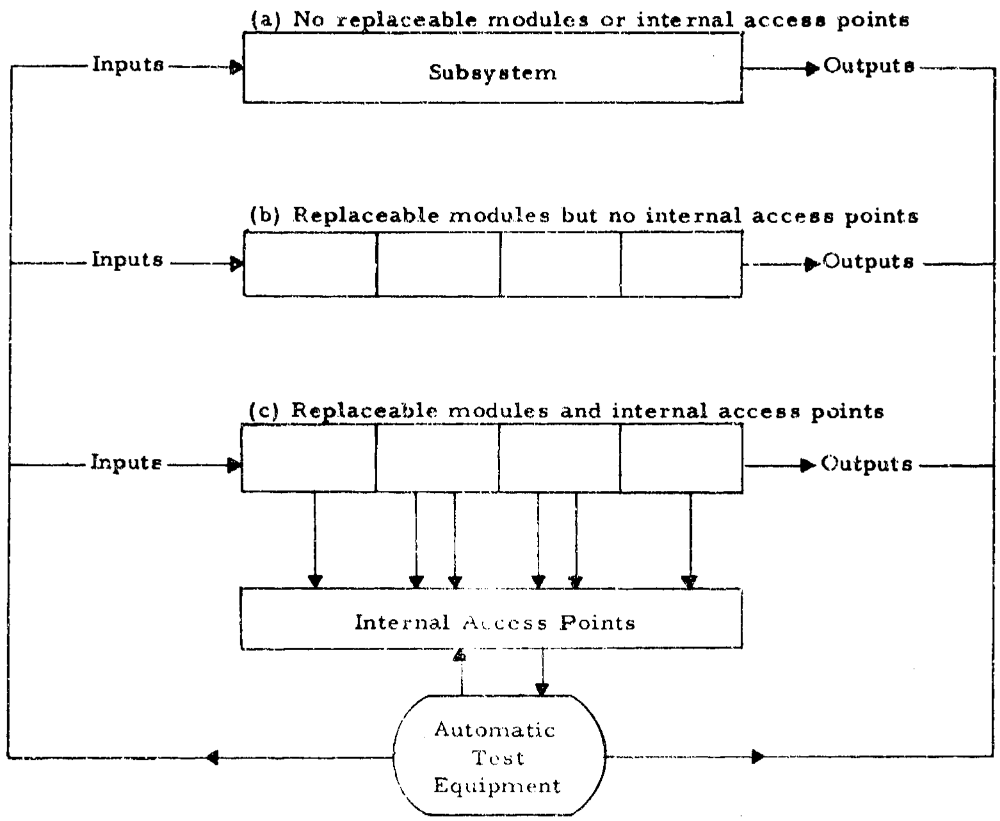
For navigation, several alternatives and combinations thereof are feasible: inertial, hyperbolic radio, etc. Each carries with it specific implications for function assignment.

2.3 Subsystem Design Concepts

It is at this decision stage that design variables begin to affect function assignment. For example, a navigation subsystem must operate in real time, using inputs from various sensors and providing continuous accurate data on position, velocity, and attitude. The different navigation sensors may require the employment of mechanical, electromechanical, or electrical techniques. Navigation data processing may be more or less automated and may require combinations of digital and analog techniques. Each possibility implies specific function assignment problems.

As a more detailed example, let us consider design for maintainability and examine the effects of two alternative design concepts, namely, Modular Design and Centralized Access Points (i.e. , brought out to a central location in a single cable. Fig. 2-2 indicates the nature of this decision problem. As a given subsystem is subdivided into an increasingly greater number of replaceable functional modules, the following consequences will generally accrue for the case where at least one access point from each module is brought out to a central location:

- Decreased reliability or lower mean time between subsystem failures (more connectors, wiring, etc.).
- Increased weight.
- Larger cable diameter and number of wires.
- Less checkout sophistication required. Instead of carrying out tests (using a few access points) requiring solution of complex simultaneout equations, it is possible simply to signal-trace through successive module access points to determine existence of failure.
- More complex internal switching in the automatic test gear.
- Decreased trouble-shooting time due to ease of sequential signal-tracing.



In (a), with no replaceable modules or internal access points, operability checks only can be performed, so that checkout requirements are simple and brief and can probably be done manually. In (b), with replaceable modules but no internal access points, checkout and trouble isolation to a replaceable unit requires very complex automatic test equipment capable of solving simultaneous equations; these functions generally cannot be performed manually. In (c), with both replaceable modules and internal access points, checkout and trouble isolation to a replaceable module are simplified because simple input-output operability checks can now be done on individual modules (or small groups) in a rapid sequential manner. Whether these checks should be done by man or machine now depends entirely upon system-specific requirements, such as speed and accuracy, and upon operational-use considerations, such as availability of trained personnel.

Fig. 2-2. Effect of modular design and test point policy upon monitoring and checkout gear

Obviously the number and location of access points in the Polaris missile is a crucial design decision which is really independent of modularization. As such, it has many consequences and requires the specification of design guidelines for functional modularization based upon trade-offs between prime and test equipment design.

2.4 Design Constraints

In this category we include such factors as cost, wieght and space, safety, survivability, state of the art, and human limitations which dictate the assignment of certain types of functions to men or machines. In navigation, real-time continuous computation of position (if required) must be done by automated means because of human limitations with respect to computational speed and load. Similarly, rapid sequential launching of missiles in normal operation must be done automatically because of the large number of parameters and the high data rate involved.

We have already discussed the effect of missile accessibility limitations upon missile checkout and maintenance capability requirements (see previous discussion under System Type). One hardware state-of-the-art limitation in maintenance is that of wave-form analysis and interpretation, which at present is most easily and least expensively done by a properly trained technician.

3 Use-Determined Factors

3.1 Base or Site Considerations (Table 2-3 A)

For any given weapon system, the basing or type of launch site or platform will impose a number of additional requirements and constraints upon development alternatives. At a hardened distributed ground-based ICBM site where a number of subterranean silos may be geographically separated by distances approximating a mile or more, state-of-the-art constraints might eliminate the possibility of completely centralized fire control and missile checkout equipment, in which case, separate equipments would be required for each missile, perhaps with some overlapping capability. But now the planner would want to consider carefully the possibility of using the same equipment for both fire control and targetting detailed periodic and pre-launch checkout using different programs (manual or automatic) and criteria in each case. In an FBM submarine, however, it is possible to time-share a single fire control subsystem among all 16 missiles for the fire control, targetting, and checkout functions.

Table 2-3A
Examples of Use-Determined Factors

Base or Site Considerations	Quantity	Deployment	Environment	
			Physical Stress	Psychological Stress
Sea-Based	Number of System Elements per Location	Location of Distributed System Elements (Operations, Maintenance, Logistics Considerations)	Humidity	Motivation
Land-Based			Noise	Morale
Hardened			Vibration	Danger/Safety
Soft	On-Line Redundancy		Acceleration	Time Pressure
Distributed	Other		Temperature	Information Load
Compact		Geo-political Considerations	Pressure	Mission-Induced Stress
Forward Area			Atmospheric Composition	Task-Induced Stress
Continental US				
Air-Launched				Failure-Induced Stress
Orbital				
Other				

Weapon System Development Cycle (Direction of Increasing Specificity) →

3.2 Quantity

Such considerations as number of weapons, on-line redundancy, etc. are often predetermined by preceding considerations in the planning cycle.

The number of Polaris missiles per FBM submarine was selected as a compromise based on trade-off considerations involving number and cost of submarines, strategy of operational deployment for submarines with respect to enemy target locations and probable search capability, and achievable missile range for a configuration containable within submarines. The periodic and pre-launch checkout equipment parameters were largely determined by missile firing rate (limited by state of the art) and specific nature of the various subsystems. It is important to note here that the second generation of FBM submarines is capable of an increased missile firing rate, which in turn has necessitated a change in targetting techniques and in pre-launch checkout requirements.

3.3 Deployment

The distance between the location of maintenance and/or checkout gear and personnel and the location of the equipment to be maintained can set important constraints on checkout and design requirements. Even more obvious is the effect of distributed locations of system elements upon logistics requirements and upon command/control and communications requirements.

3.4 Environment

3.4.1 Physical

State-of-the-art limitations at any given time will often combine with system performance requirements to dictate a system operating environment which is incapable of supporting human life (for example, an unmanned satellite-launched weapon). Such instances will normally result in a class of non-allocatable functions, i.e., a class of functions which can be performed only by automated means. In less extreme cases, atmospheric conditions may affect the allocation decision. For example, carrier-based aircraft flight-line checkout in extreme environment (cold, noise, etc.) should not require extended exposure of personnel. Thus, the allowable exposure time for humans in extreme environments may become a determinant in function allocation. When manual operations exceed this time, some functions must be automated.

3.4.2 Psychological

In addition, there are the more subtle psychological stresses which will often degrade the usefulness of checkout equipment in the field. There are elements of both danger and "time pressure" in pre-launch operations associated with ballistic missiles and in carrier landing operations which may degrade man's ability to make complex decisions accurately and with the required timing. The effects of both psychological stress and so-called "task-induced stress" (i.e., the effect of "loading" the operator) on human performance in varying types of tasks and system design situations are well documented in the psychological literature[8, 12, 13, 19, 22].

One further psychological concept deserves special consideration at this point. The effects of varied levels of motivation and morale upon operating and maintenance effectiveness can be very great. In reviewing relevant literature in this area, we find that low levels of motivation and morale are found to be associated with two kinds of function <u>mis</u>-allocation:

1) Where equipment requires high skill levels on the part of low skilled personnel.

2) Where equipment requires low skill levels on the part of high-skilled personnel.

Note that these are not necessarily simple man-machine mismatches due to bad selection, training, or assignment of personnel. Rather, they are largely design-controllable in the following sense:

> The first instance [1) above] involves equipments which are designed such that only simple manipulative and gross decision functions are required of the man, and personnel are selected and trained on this basis. However, in practice, the frequent occurrence of unpredictable or medium-probability events may often require decisions and actions beyond the capabilities of these personnel, resulting in lowered morale.
>
> The second instance [2) above] may be characterized by the situation in which field operating, maintenance, and decision problems are adequately anticipated and personnel selected and trained to handle medium- and low-probability events (note that this almost always requires a detailed knowledge of both weapon system and use factors). Thus, given the same general types of equipment design as described in 1), above, these personnel are dissatisfied with "goon meters" and bored with simple monitoring tasks. Motivation can be expected to degrade as a result.

In both instances, the results take their toll in distrust of equipment and "sloppy" procedures. These, in turn, result in increased errors, down time, and spare parts use rate, and decreased system operability and availability. In both instances, system design concepts which recognize these use-determined factors can serve to eliminate the undesirable results. Subsystems should be so designed that personnel are kept continually involved in system functions, to a level consistent with their capabilities.

3.5 Management Policies (Table 2-3 B)

Operations management policies include the command/control structure and existing SOP within which a weapon system must operate and the intelligence, communications, and data processing milieu which determine and shape its inputs. Weapon system design must go beyond simply interfacing with the appropriate equipments; it must also take into account the basic nature of the superstructure in which it will operate.

Maintenance management and/or system support policies include the planning, scheduling, and controlled provision of spare parts, test equipment,

technicians, TO's, field modifications, manufacturers' tech reps, and so forth. Although definitely affected by equipment design (e.g., type and number of spares are directly influenced by modular design and part failure rates), maintenance and support management policies include external use-determined factors to which a weapon system is most vulnerable. The organizational aspects of weapon system checkout and maintenance are fairly complex.+ However, it is clear that decisions concerning the employment and man-hour utilization of manufacturers' tech reps, for example, will have consequences in the areas of system down time and checkout effectiveness. The local base procurement allowances for spare parts and test equipment will have similar effects.

Table 2-3 B
Examples of Use-Determined Factors

MANAGEMENT POLICIES				
Operations	Maintenance			Support
Operating Levels	Maintenance Levels			Support Levels
Command/Control	In-Flight	Ship	Spare Parts	Planning
Operational	Flight Line	Tender	Test Equipment	Logistics
Communications and DPS Requirements	On-Line	Depot	Field Mods	Failure Reporting
Other Factors	Off-Line	Factory	Navy Technicians	Other Factors
			Tech Reps	
			Overhauls	

Distribution of the above functions among distributed system elements and levels

Weapon System Development Cycle
(Direction of Increasing Specificity)

In the other direction, the ever-present necessity for field modification to equipment already in operational use must be taken into account when allocating functions between man and machine. The field modification (or "SPALT") problem for the FBM system was an important factor in considering two alternative proposals for mechanizing checkout of Launcher and Fire Control subsystem modules. The two proposals differed in that one used a punched paper tape program

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+ For an example of such an analysis, see Wohl, J. G., et al (23)

and was largely automated, while the other employed a punched card technique to aid the operator in a primarily manual situation. Since a cannister of tape might contain test programs for upwards of a dozen different module types, the normal process of field substitution of an "improved version" of a particular module type would require that an entirely new tape cannister accompany the arrival in the field of each newly revised module type. In contrast, it would be a relatively simple and inexpensive matter to package an appropriate punched card with each module sent to the field. The logistic, accounting, and program updating requirements consequent to this kind of decision obviously would be quite different in scope.

Selection, training, and assignment of personnel have already been discussed with respect to man-machine mismatch and psychological stress. Suffice it to say at this point that the mismatch can just as well result from inadequate system management policies as from inadequate design.

4 Man-Machine Factors

The development to this point has been concerned with the way in which successive constraints become applied to the assignment problem during the weapon system development cycle as a function of system planning, design, and operational employment considerations, thus progressively reducing the degrees of freedom available for function assignment. The final set of factors which must be considered includes the capabilities and limitations of men and machines relative to the activities which they must perform in various Naval tasks. The following discussion is, therefore, divided into four parts:

- Human task trends in Naval weapon systems.
- Description of fundamental man-machine tasks and task elements.
- Definition of man-machine interface.
- Discussion of capabilities and limitations of man and machine.

4.1 Human Task Trends in Naval Weapon Systems

More often than not, as has been demonstrated, the general design requirements of the system will suggest the number and location of personnel. They will not, however, suggest how personnel can be utilized most effectively. One general trend in the evolution of the FBM system (and other complex systems, for that matter) should be noted in this connection and its implications for the role of human operators pointed out: Systems are moving in the direction of requiring larger and larger amounts of data to be more and more accurately

processed in increasingly shorter periods of time. The human has rather severe limitations on the amount of information (1) to which he can respond, and (2) which he can process accurately within a short period of time. Therefore, the trend has been to increase the degree of automation of systems. However, this trend has not succeeded in removing the requirements for man in the system, but has merely shifted his responsibilities to other areas (e.g., performance monitoring, manual backup, complex decision making in unforeseen contingencies, computer programming, etc.). Also, as equipment increases in automaticity, larger numbers of more highly skilled maintenance technicians are usually required, thus increasing the amount of attention which must be given to the design of equipment for maintainability.

Some of these trends for non-military personnel are clearly indicated in Fig. 2-3, which shows how the per cent distribution of the total U.S. civilian labor force has changed since 1900 among five broadly defined categories of human jobs:

- Managerial
- Semi-skilled
- Highly-skilled
- Unskilled
- Agricultural

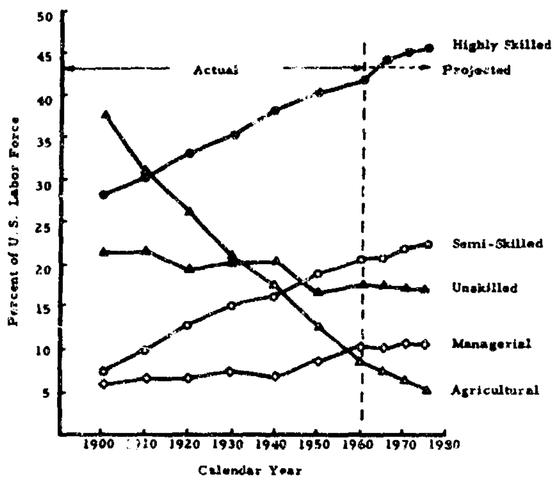


Fig. 2-3. The changing composition of U.S. civilian labor force: 1900-1975 (Source: Economic Almanac, 1962; based upon 1960 census data)

If we can assume that the actual labor force distribution is closely related to industry needs, then Fig. 2-3, which is based on census data, indicates that the need for agricultural workers has declined markedly since 1900; that the need for unskilled labor has undergone a gradual decline; and that the need for semi-skilled labor has gradually increased. Most important, however, is the fact that Fig. 2-3 shows a rapidly growing need for highly skilled personnel and a steadily rising need for managerial skills.

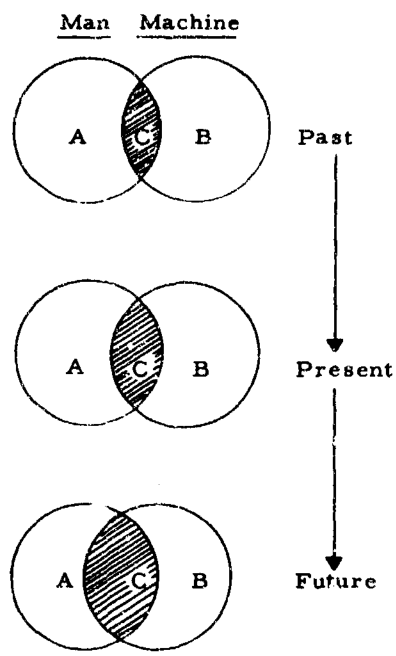
The drastic reduction in need for agricultural workers, of course, may be traced directly to the results of automation, as may the reduction in need for unskilled labor. On the other hand, the rapidly increasing requirements for highly skilled labor may also be traced largely to automation; for to the extent that automation in an industrial "system" eliminates unskilled labor requirements, it upgrades the skill requirements for the personnel remaining in the system.

The same general trends must operate within military weapon system development. In fact, it is likely that military weapon systems lead the trends indicated in Fig. 2-3 by 8 or 10 years. For example, during World War II, ammunition handling was automated in several of the shore bombardment and anti-aircraft gunnery systems used on board heavy ships. This eliminated the need for certain classes of unskilled and semi-skilled labor. Toward the war's end, gun fire control computations were automated (e. g., the MK-I computer), eliminating the need for certain semi-skilled and highly skilled gun laying activities. The development, during the same period, of automatic radar tracking for gun fire control systems resulted in elimination of the highly skilled tasks of optical tracking and range finding. Finally, we have only to look at the few hundred square feet of combat information center on the heavier World War II ships and compare it with the thousands of square feet of command and control space on the Enterprise to see what is happening to certain high-skill and managerial functions in modern Naval weapon systems.

The FBM system is an excellent example of the result of these trends. Analysis of the crew duties and ratings indicates that approximately 15% are managerial decision makers, nearly half perform highly skilled operating and maintenance activities, about one-fourth perform various semi-skilled duties, and the remaining 10% are unskilled (mess personnel and non-rated personnel).

This section requires some care in its application. Most of the information on the utilization of man is often applicable only to gross categories of functions. For some functions there is no problem in assignment; they can clearly be performed more effectively by man or by machine, but not by both -- at least at a given stage of technological development. But for many functions, there is considerable overlap; and the decision to use man is contingent on considerations

specific to the particular system, including the stage of development. The following paradigm indicates how this situation will change with time. Areas A and B indicate, respectively, the sets of Naval tasks which can be performed by man and machine, while the overlap, Area C, represents those tasks which can be performed by either man or machine.



As state of the art (Area B) progresses and machines become increasingly capable of performing human activities, the overlap (Area C) will increase and the distribution of skills in Area A will change in accordance with trends shown in Figure 2-3.

Hence, because of this continual change, only general guidance can be provided, along with some of the considerations involved in making decisions about utilization of personnel. This guidance cannot replace the judgment which must be exercised by systems and human factors engineers working together as a team to develop and evaluate alternative system design concepts. However, one over-riding consideration should be borne in mind: A well-integrated man-machine design can achieve far more than either man or machine alone.

4.2 Fundamental Man-Machine Tasks and Task Elements

For convenience, we have grouped the various types of Naval functions which can be performed by man and/or machine into several categories:

. Decision tasks

. Operating tasks

. Checkout, maintenance, and damage control tasks

. Administrative and clerical tasks.

This classification scheme is carried further in Table 2-4, which identifies basic task types within each of these categories and the human skill requirements if performed by man.

Table 2-4
Man-Machine Tasks in Modern Naval Weapon Systems

Task Category	Skill Requirements If Done by Man
Decision Tasks	
. Operational Decisions	semi- or highly skilled
. Tactical Decisions	highly skilled
. Strategic Decisions	highly skilled
. Policy Decisions	highly skilled
Operating Tasks	
. Materials Handling and Processing	low or semi-skilled
. Continuous Control	highly skilled
Periodic, or Discrete, Control	semi- or highly skilled
. Monitoring	semi- or highly skilled
. Data Processing and Computation	semi- or highly skilled
. Communication	semi-skilled
Checkout, Maintenance, and Damage Control Tasks	
. Preventive Maintenance	semi-skilled
. Test and Checkout	highly skilled
. Diagnosis	highly skilled
. Fault Isolation	highly skilled
. Restore, Replace or Repair	semi- or highly skilled
Administrative and Clerical Tasks	
. Planning	highly skilled
. Scheduling	highly skilled
. Reporting	semi-skilled

Regardless of the classification scheme employed, however, it must be recognized that there exist basic task elements which are common to every task, whether performed by man or machine or by both together. The three basic functional "building blocks" of which any set of system tasks or activities, is composed are simply:

. Sensing

. Processing

. Actuating

These building blocks, or task elements, are summarized in Figs. 2-4 A and B, which also indicate the functional components of which they are composed. Figs. 2-4 A and B emphasize the similarities between man and machine; in the following discussion, important differences will also be noted. (For discussion of "decision making" vs. "processing," see footnote on pg. 38.)

These functions admittedly are an oversimplification of complex system functions, be they man or machine; nonetheless, they will be useful as background to the guidelines on assignment of functions. Some qualifications should be added at this point; any complex system involves many combinations and replications of these basic functions. Also, man and machine functions are not completely analogous, nor can one be completely substituted for the other -- at least at the present state of technological development. This is demonstrated in Table 2-5, which describes various possible levels of automation in both mechanistic and humanistic terms. The areas of non-correspondence are quite evident. Finally, it should be noted that the terms "equipment" and "personnel" are used differently to distinguish between two major types of components of complex semi-automatic or automatic hardware systems. Obviously, any item or group of hardware which can perform more than one function and which is designed to accomplish some common objective can be referred to as a system. The same can also be said of man, since he is sufficiently complex to be referred to as a system and as being composed of many subsystems. As yet, no complex equipment system exists which is fully automatic; that is, no complex equipment system is completely independent of man in all phases of its operation and maintenance.

The man/machine functions of sensing, processing, and actuating, together with their interrelationships, will next be discussed in detail.

Table 2-5
Analog Between Personnel and Equipment Functions+

Level of Functioning	CHARACTERISTICS Equipment	Personnel	Personnel Level of Functioning	Personnel Capabilities Involved
Zero Order	Tools supplied to man to increase his efficiency but not to substitute for human function (e.g., hammer, screwdriver, knife, pliers).	All human energy and control expended as required.	Physical strength and characteristics (e.g., strength, endurance, etc.).	. Human force expenditure . Human size (physical) . Human response to environmental conditions
First Order	Equipment power complements human energy, replaces much of the human work energy, but requires control and direction by an operator.	Human energy used to control, direct, and apply some type of powered equipment.	Sensori-motor capabilities.	. Sensori-motor capabilities -Reaction time (time lags) -Speed of manipulation -Positioning . Skill vs aptitude
Second Order	Equipment power replaces human energy but requires operator set-up and start and stop control.	Human energy used to start and stop and set up machine work.	Sensori-motor capabilities.	. Control-display dynamics -Tracking behavior (pursuit and compensation) -Aided tracking -Quickening . Aging
Third Order	Equipment cycling or sequencing is self-ordered but not self-corrected (open loop).	Human controls of machine cycles required.	Sensori-motor capabilities	
Fourth Order	Equipment cycling and sequencing is self-ordered and self-corrected (closed loop)	Human monitors machine performance.		. Vigilance . Psycho-physical coding, etc. . Stimuli
Fifth Order	Machine performance is based upon automatic solution of control equations.	Performs calculations often with elaborate language, symbology.	Mental functions	. Memory . Learning . Intelligence . Intellectual habit patterns

+ After George and Amber(9)

Table 2-5 (cont'd)

Level of Functioning	CHARACTERISTICS Equipment	Personnel	Personnel Level of Functioning	Personnel Capabilities Involved
Sixth Order	Machine performance is based upon automatic solution of control and contingency equations.	Obeys complex logic, reasons by inductive logic	Hypothetico-deductive reasoning	. Concept formation . Information synthesis and processing . Communications . Language and vocabulary
Seventh Order	Performance is a function of experience both with the present task and with a history of similar experiences (which, presumably, are stored in memory). In this case, equipment avoids past mistakes, attempts different forms of operation, and improves. Examples of experimental equipment in this level are the "Perceptron" and the "Cybertron."	Performance changes as a function of learning.	Learning	. Complex learning . Learning as a directed process of change (motivation, need, life crises, etc.) . Attitudes . Training for desired performance -Motor -Concept . Age differences . Individual differences . Conditioning
Eighth Order	Equipment extrapolates from its experience to modes of operation beyond actual experience, resembling intuitive and judgment activities.	Obeys complex logic, utilizes intuition and judgment, reasons by deductive logic.	Inductive reasoning	. Imagination . Creativity . Group dynamics (leadership)
Ninth Order	Equipment develops original creative concept and can work beyond its programming. No machine of this type now exists and there probably would be little agreement on what constitutes creativity in the mechanical-electrical sense.	Creates, originates	Imagination, channeled emotion	. Motivation and morale value structures
Tenth Order	Equipment relates socially with other equipment and with personnel. Equipment is capable of diminant interactive behavior.	Personnel relate socially with one another and are capable of various roles (dominant, submissive, etc.) at various times.	Interpersonal relations and social living	. Social behavior . Group dynamics . Morale

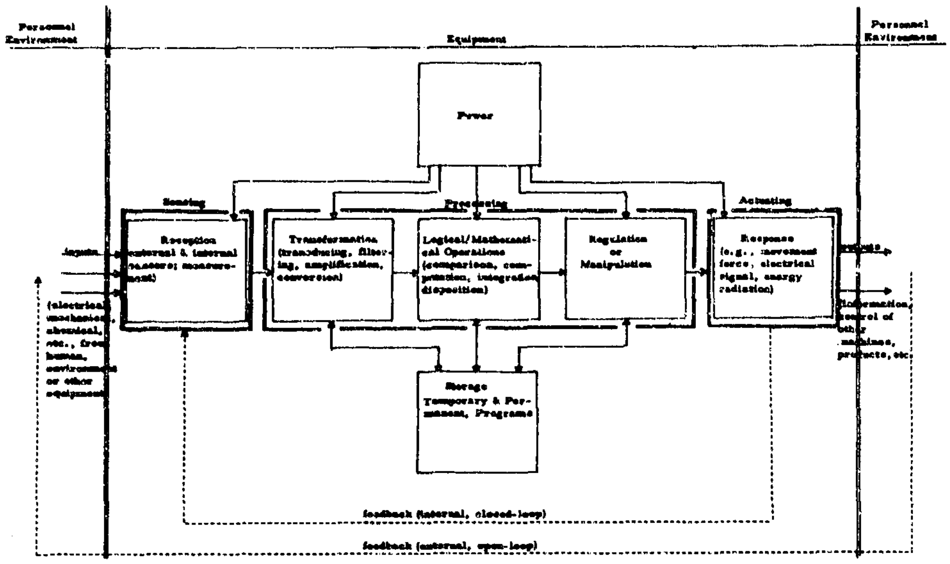


Fig. 2-4A. Generalized functions of equipment

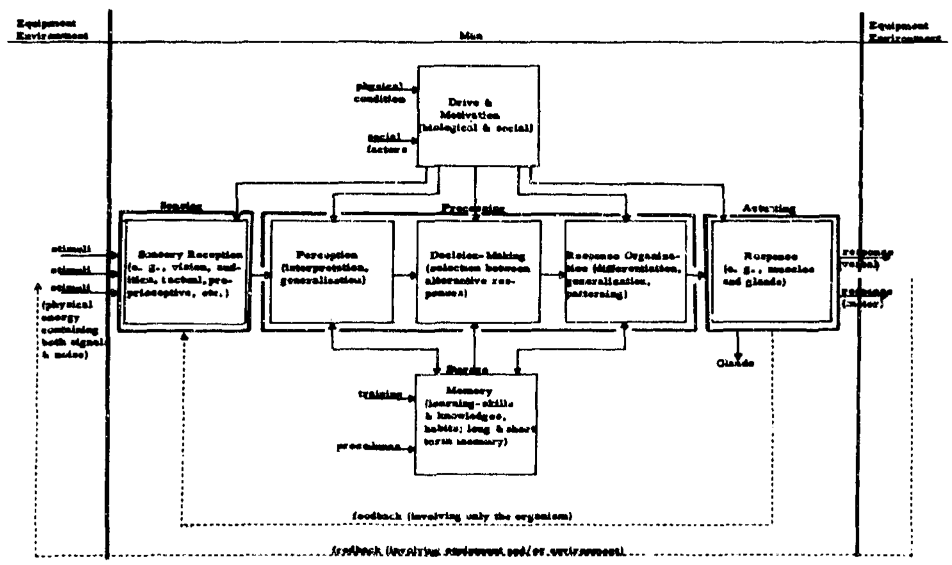


Fig. 2-4B. Generalized behavioral functions of personnel (single person)

4.2.1 Sensing

The sensing function consists of the detection of some physical energy (information or signals) originating within the environment of a system. These signals may originate external to the system, as in radar or sonar returns or as in the human senses of vision, hearing, smell, etc. They may also be developed internal to the equipment, as in the result of switch closures in equipment or the kinesthetic sense in man. In either case, specific sensors are required to receive these signals as inputs to the system. The sensing function is often coupled with transducing, converting, filtering, or amplifying functions. Equipment examples abound, as in the transformation of a mechanical signal to an electrical signal, analog to digital conversion, selection of some portion or all of a signal for amplification, or screening out some undesired portion of a signal component, e.g., noise.

An important characteristic associated with human senses is the phenomenon of attention. Although the human being is constantly receiving sensations from many sources, he is able to select and concentrate on only those which are of importance to him, much as equipment sensors are able to filter out various unwanted signals or noise or to select desired signals. In addition to attention, the reception of stimuli is influenced by a man's physical condition (i.e., health, fatigue) as well as by the range of sensitivity of the receptors.

The phenomenon of attention is closely related to the concept of perception. Human reception of signals would be meaningless without some basis for their interpretation. This interpretation becomes possible as a result of experience or learning. For example, the onset of a red light may be interpreted through learning as an emergency condition which, in turn, becomes associated with certain responses. Ability to associate through learning takes another form, too; for example, the red light may often occur simultaneously with a siren. Later the presence of the siren alone may cause a recollection of the red light and trigger the "red light" responses, whether desirable or not. This association demonstrates another characteristic of human perception, that of the symbolic processes associated with it. Through man's ability to abstract significant details of complex inputs and to remember them, he is able to apply his experience to other situations; i.e., he is able to learn. Unlike equipment, perception in man is also influenced by emotional processes. For example, the performance of a particular task may be enhanced or degraded depending on the pleasant or unpleasant memories associated with it.

Thus, the function of perception in human beings is somewhat similar to those of transducing, filtering, and amplification in hardware systems.

4.2.2 Processing

After the information has been transformed into inputs suitable for use in a system, it is processed to produce appropriate outputs. The information processing function may involve any or all of the following subfunctions: (1) measuring (estimating) and comparing external signals against each other or some stored standard of comparison; (2) integration of various signals with each other and with various alternative available actions; and (3) storage of some or all of the information, to be acted upon later. Transducing, converting, amplifying, and filtering again may be involved. Information processing in equipment may be performed according to pre-established fixed programs or may be under the control of a human operator. Often the rate at which information is received or can be processed is too great for the information to be acted upon immediately, or it may be unnecessary to act upon the information at the time of reception. In these cases, data may be stored either temporarily or permanently, depending on the requirements for their utilization. In equipment memory there may also exist programs which provide instructions for processing the information.

Man is able to process information based on his perception of the signals which he receives and upon stored information. This integration of external and internal information as the basis for identification or selection of appropriate courses of action is often called decision making. Although decision-making tasks reflect an emphasis on only certain aspects of human information processing capabilities, they have become a focal point for discussing man's processing capabilities.+ The processes which support the decision-making

+ To many, the general concept of "decision making" entails a necessary ingredient of mystery, i.e., the choosing of one among two or more alternatives necessarily requires that the chooser does not have complete information at hand. As an example, we talk of a submarine skipper having to make a complex decision. He must make his choice based on a number of elements to which he must assign a variety of differential weightings. Either the weightings and/or the population of elements is incompletely known to him. In addition, he may not know the proper model or series of manipulations to use in order to make the best choice. This is a prevalent conception of "decision." The man does not have all the necessary information and/or knowledge, yet he must make his choice now. He says, "I can't wait to learn that; I'll have to make a decision." The corollary to this conception is that if the man does have all the required knowledge and information, then the logical choice becomes self-evident and there is really no decision involved. This popular conception of decision making is refuted herein. The term "decision" is utilized in this volume as a descriptive noun for an activity which can be performed by man or machine which may or may not involve sensing and actuating, and which always involves processing. The term as used herein describes the process of selection from among alternative courses of action; alternatively, it describes the process of "mapping" input sets upon output sets. Thus, it is correct to talk about "having made a decision" (past tense); but when a man "is deciding" (present tense), he is processing.

capabilities of man include abilities for qualitative estimations, comparisons, judgment, transformation, coding and decoding, inductive and deductive reasoning, abstraction and conceptualization, memorization and recall, and prediction. The result of these capabilities is to make man much more flexible as a data processor than machines -- at least with the present stage of technological development. Through appropriate training, man is able to deal with changing situations and unforeseen problems in the absence of a specific program. Unlike a computer, man can continuously develop and modify his own programming. In other words, he can learn. Closely associated with man's decision-making function is his memory or storage capability. Memory is the retention of what is learned and, conversely, forgetting is the failure to retain what is learned. Without memory, at least in the biological sense, there could be no learning; each occurrence of a signal would elicit the same response as before and there would be no modification or reprogramming of behavior. The capability of man to remember and to modify his behavior through learning accounts for much of his flexibility as a programmer of computers. Much of what is remembered and the ability to manipulate and combine this information (thinking and reasoning) is the result of man's symbolic processing capability. What is retained is in the form of words, numbers, or images which represent abstractions or symbolizations of what is learned. This capability for abstraction and conversion to symbols of large amounts of information accounts for much of man's superiority over machines in decision making.

4.2.3 Actuating

Once a desired action has been identified or selected as a result of information processing or decision making, it is necessary to implement this action. This may involve the function of regulation such as controlling the rate and time at which the action is performed (e.g., the duration of the ballasting operation in diving the submarine, or control of the speed of the submarine). Other discrete forms of control may be involved (e.g., the selection of "Channel 1" vs. "Channel 2" in the Fire Control Subsystem, or the transmission of information to the missile guidance capsules at an appropriate time in the firing sequence). Regulation in man involves the organization or patterning of his responses so that they will occur at the proper time, in the proper sequence, or in the proper combinations. For example, when learning to perform a procedure, an operator must refer to manuals or otherwise seek guidance to learn how to perform the procedure. Eventually, these responses become sufficiently learned that the procedure is performed rapidly and accurately as a perfected and completely organized skill without any external supports. As skills are mastered, they are performed more and more automatically and involve less conscious effort or thought on the part of the individual. This is particularly evident in the learning of sequential responses, as in keyset operation, or continuous responses, as in steering or tracking. For the learning of complex knowledge, as might be required for high-level

decision-making tasks, a similar organization of responses may take place if similar situations occur often enough; otherwise, man may exhibit considerable variability and disorganization in his behavior.

Also related to the regulation function in systems is the concept of feedback. Many semi-automatic or automatic devices or systems have one or more sensing or monitoring circuits which feed back information on the operation of the system to provide a basis for regulation and further action. Such feedback loops are the distinguishing feature of closed-loop systems as opposed to open-loop systems. In many systems a human operator or monitor is depended upon to close the loop. Responses within the human himself, as with closed-loop hardware systems, exhibit feedback characteristics. This is generally referred to as knowledge of results and may be of two general types: internal, resulting from sensations associated with bodily movements or the higher mental processes, as might occur in the mental solving of some problem; and external, resulting from seeing or hearing the results of his responses such as the change in position of a control, change in the status of an instrument, or change in position of a vehicle.

Finally, to achieve the output -- whether it is information, materials, or control of other equipment -- all systems have one or more actuation functions. These require a supply of requisite energy in a form necessary to achieve the output. In man, this final phase of the behavior process is the evocation of some muscle response, either verbal as a command, or as a motor response such as the movement of the arm and hand to activate a control or the movement of the eyes to view some display. Glandular responses also occur but ordinarily are of less importance from a design standpoint; however, they do affect the level and type of activity of the individual as well as his comfort.

Two other categories of functioning peculiar to humans should be mentioned, those of drive and motivation. Drives include such factors as hunger and thirst and are related to the physiological requirements of the human organism. Motives are requirements which arise out of the individual's learning experiences, primarily those involving interaction with other people. Both drives and motives function as energizers of human behavior and as such are somewhat analogous to the power required by hardware systems for activation (see Figs. 2-4 A and B).

4.3 The Man-Machine Interface

Since the concern in this volume is with complex subsystems of the FBM Weapon System in which many personnel and equipments are involved, it is important to describe the interactions between men and machines, particularly as

they relate to control and display interfaces. The simplest situation which can be described to indicate the significant interactions is that of one man and one machine, as in Fig. 2-5.

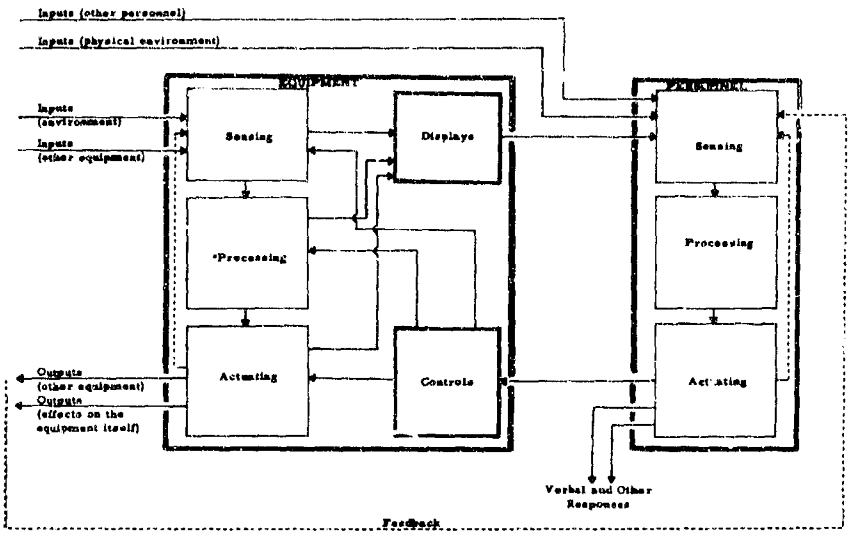


Fig. 2-5. Man-machine system

From Fig. 2-5 it is evident that the machine can receive inputs from the environment, from other equipments, from feedback within itself or from the man through the control link or interface. Man can receive inputs from other personnel, from the physical environment, from the equipment itself through displays, or, in some instances, from the actual outputs of the equipment itself (e. g., ship motion).

Fig. 2-5 suggests that processing can take place within the equipment or between the equipment and man through the links provided by displays and controls. However, simpler situations occur where man may do all of the processing; or, if the equipment is as simple as an instrument, man can perform all of the processing and actuation; or if it is a hand tool, man will provide the sensing and processing and part of the actuation.

Fig. 2-5 indicates that a machine may respond by providing outputs to control other equipments (some may even control man); exert some control on itself such as movement, or provide outputs in the form of materials or products, such as the print-outs provided by line printers. Similarly, human outputs in response to input data may be used to control other equipment or other personnel, depending on the information received, the equipment displays, the environment, or feedback from the outputs of the equipment.

The simple one-man/one-machine relationships described above represent only part of the problem of designing equipment for human use. The major part of the problem is the multiple-man/multiple-machine case where there are many equipments performing different, or sometimes redundant, functions and many men each also responsible for different functions. The problem is the consideration of the possible functional relationships among personnel and between the men and machines in addition to the functions to be performed. In short, an entire assemblage of components, man and machine, must be considered before even preliminary decisions can be made about the assignment of functions and the control-display (i. e., man-machine interface) characteristics which will be required for the personnel to perform their functions effectively.

4.4 Capabilities and Limitations of Man and Machine

Table 2-6 summarizes the relative advantages of men and machines with respect to the basic task elements just discussed. Since this represents the final set of factors to be considered in weapon system development and man-machine function assignment, it will be expanded upon in some detail below.

Following is a series of general principles taken primarily from discussions by Swain and Wohl (24) after Fitts (6), together with some additions and comments pertinent to the assignment problem in general.

4.4.1 Characteristics Tending to Favor Humans over Machines

4.4.1.1 Ability to Detect Certain Forms of Stimuli

The ability to detect certain stimuli (e. g., smell, taste), especially stimuli which are not readily sensed inorganically, is one of man's characteristics.

4.4.1.2 Sensitivity to a Wide Variety of Stimuli

Man is sensitive to a wide variety of stimuli through the use of

the organs of sight, hearing, smell, touch, temperature, pain, taste, balance, and muscle sense (kinesthesis). All of these sensory abilities are used in operating and/or maintaining equipment, though obviously some are used much more than others. In spite of this wide variety in sensitivity, the precision of sensitivity in any one mode is quite restricted compared to machine "sensing ability."

Table 2-6
Summary of Significant Man-Machine Factors

Advantages of Humans	Task Element	Advantages of Machines
Detect low levels of energy Sensitivity to a wide variety of stimuli Perceive patterns and generalize from them Detect signals in a high noise environment	SENSING	Sensitivity to stimuli outside of man's ability Insensitivity to extraneous factors Monitoring of other machines or men
Store and recall large amounts of information Exercise judgment Improvise and adopt flexible procedures Handle low-probability events Arrive at new and different solutions to problems Profit from experience Track under a wide variety of situations Perform when overloaded Reason inductively	PROCESSING	Respond quickly to control signals Store and recall large amounts of data for short periods Computing ability Handling of highly complex parallel operations Deductive logical ability
Perform fine manipulations	ACTUATING	Perform routine, repetitive, precise tasks Exert large amounts of force smoothly and precisely

4.4.1.3 Ability to Perceive Patterns and Generalize About Them

Man has this ability, even though the patterns may change in size or position or may be partly masked by noise. However, this ability (perceptual constancy) as it applies to certain types of activities is often difficult to learn. Interpretation by human operators of patterns of lights sometimes required by certain computer programs may be extremely difficult to learn. Waveform analysis is considered by most maintenance technicians to be the single most difficult perception required in test and checkout, and differences of opinion often exist between technicians in interpreting waveforms. Therefore, it is ordinarly advisable to search for ways to avoid waveform or light pattern analysis, especially where relatively low-skilled personnel may be employed. However, if data can be encoded and displayed in such a way that the personnel can use their perceptual capability to the maximum (i. e., if adequate "pictorial" or familiar "patterned" displays are used), then they will be very good at sizing up complex situations quickly.

4.4.1.4 Ability to Detect Signals (including patterns) in High Noise Environments

This ability is related mainly to the use of various types of operational cathode ray tube displays and to reception of auditory signals. One shortcoming to this human ability is the human tendency to fill in gaps in the displayed information on the basis of expectancies. When these expectancies are not valid, the human operator or technician may see something that is not there or may miss out-of-tolerance indications not in line with his erroneous expectancy. This human limitation applies mostly to monitoring tasks, somewhat less to routine operating and maintenance tasks, and least to trouble location tasks where the man knows something is wrong and is searching for out-of-tolerance indications.

4.4.1.5 Ability to Store Large Amounts of Information for Long Periods and to Remember Relevant Facts at the Appropriate Time

This ability is related to the human's superior ability to use judgment, to improvise, and to respond appropriately to low probability occurrences. The human is said to be capable of storing from 1.5 million to 100 million binary bits of information. The largest computers available fall far short of this capacity. Man's memory of facts is less reliable than machine's, but he does fairly well at remembering principles, strategies, contingencies, and other rules and their applications, provided that he has been properly taught.

4.4.1.6 Ability to Use Judgment

It is difficult to define "judgment," though we all seem to know what it is. Perhaps man's superior ability to use judgment is related to his ability to handle concepts, ideas, and other data which are not easily quantified and to arrive at a decision on the basis of some unspecifiable comparison of nebulously defined alternatives, even when the situation is unique. Machines are not yet very efficient at the kind of selective, long-term storage needed in handling unique problems, and they cannot be fed any variables that cannot be encoded. Thus, judgment is very important where the population of events cannot be completely defined.

4.4.1.7 Ability to Improvise and Adopt Flexible Procedures

The human can reprogram easily and quickly and can vary performance tolerances quickly. He can acquire new methodological know-how simply by reading printed verbal procedural directions. Human flexibility helps avoid complete breakdown in emergencies. Thus, if high degrees of flexibility are required for navigation, fire control, and launch operations, then man should play an important role in accomplishing them. However, he would have to be relatively highly skilled unless the flexibility could be designed into written procedures for him to follow and allowable task durations were sufficiently large.

4.4.1.8 Ability to Handle Low-Probability Alternatives (i.e., Unexpected Events)

The human may not always employ an adequate strategy in dealing with rare events. In fact, he generally tends to try several strategies which have worked before for more familiar events, and he tends to repeat unsuccessful strategies or to just "Easter egg" (i.e., attempt random activities). This characteristic is not restricted to relatively unskilled personnel. If low-probability events can be programmed into a machine, the machine will be more efficient, because there is no forgetting. However, if the population of possible low-probability events is large (the usual situation in command/control and checkout operations), then the storage capacity required to handle them poses problems for the machine. On the other hand, properly designed procedures, coupled with adequate training, can markedly increase the average man's facility to respond to the unexpected.

4.4.1.9 Ability to Arrive at New and Completely Different Solutions to Problems

The human can employ originality in putting to use incidental intelligence picked up during his training or experience. Unfortunately, he

sometimes may try the novel when the usual would be more appropriate. This partly explains the often-observed tendency for the technician to "tinker" and for the operator to "over-adjust" rather than follow the prescribed procedures. Probably a more complete explanation should also refer to the usual inadequate design of procedures.

4.4.1.10 Ability to Profit From Experience

Ability to profit from experience, that is, to modify responses on the basis of prior events, is another of man's characteristics. It is not used to its maximum in operating and maintenance situations because of lack of a formal organization and procedure for incorporating and disseminating a body of operating or maintenance knowledge. Thus, system management policies will often prevent a system from taking advantage of experience. Although machines have been built that can "learn" from experience (e.g., chess players and maze runners), the cost and volume required for such machines is much greater than for an equivalent man."

4.4.1.11 Ability to Track (i.e., Act as a Servo Follow-Up) In a Wide Variety of Situations

Man has this capability despite relatively poor tracking ability. The ability to track (i.e., follow or center a moving target) is more pertinent to operator positions than to maintenance positions. A notable example in the FBM system is the Type 11 Periscope operator, who must center a star within the periscope field of view in order to obtain a position or heading fix. His ability to do so with adequate accuracy obviates the need for an automatic star-tracking device.

4.4.1.12 Ability to Perform when Overloaded

The human is capable of withstanding high conditions of loading that might cause a complete breakdown in a machine. That is, the human frequently can perform at a less optimum rate or at a lower level of proficiency under high load conditions, but he usually can continue to perform. This quality of "graceful degradation" is found in some machines, but to a lesser degree than in humans. However, this human ability is related to man's ability to generate his own inputs, and the negative side of this ability is the possibility that these inputs may be irrelevant to a solution. Thus, the human introduces internally generated "noise" to the man-machine system, and this can be part of the "overload."

4.4.1.13 Ability to Reason Inductively

Man can reason inductively, that is, make generalizations from specific observations. Along with judgment, this is perhaps man's greatest

claim to fame. It is especially important in decision making. But one of the reasons why inductive ability has been so important in Naval tasks is that adequate support for human deductive ability is often absent in a given subsystem (i.e., insufficient information is presented to the man). Since the generalizations made by personnel in the absense of information are so often incorrect, the best operating or maintenance situation should perhaps be so structured as to require as little as possible of man's inductive ability. (As will be seen later, this does not necessarily mean to automate.) The major exception to this statement is the set of Naval tasks which can be characterized as largely decision making in nature.

4.4.1.14 Ability to Perform Fine Manipulations

This superiority of man is especially important in assembly-disassembly operations, fault correction (e.g., soldering, replacing tubes, etc.) and in the fine adjustments required in calibration and alignment. Machines built to perform this type of manipulation are frequently extremely costly and complex. However, precise manual adjustments often must be aided by a machine, for example, a receiver tuning device or a torque wrench with a readout in foot-pounds. And those manipulations involving complex eye-hand coordination are difficult to learn to a high skill level.

4.4.2 Characteristics Tending to Favor Machines Over Humans

4.4.2.1 Sensitivity to Stimuli

Machines can sense forms of energy in bands beyond man's spectrum of sensitivity, for instance, infrared and radio waves.

4.4.2.2 Insensitivity to Extraneous Factors

Machines have a greater insensitivity than man to extraneous factors. They have no morale problems. They do what they're told to do. Perhaps this is at once the machine's greatest advantage and its greatest disadvantage. The advantages tend to be emphasized by design engineers, especially those who have seen equipment misused in the field. The disadvantages tend to be emphasized by field personnel, especially those with high levels of skill who see aspects of this skill being replaced by machines.

4.4.2.3 Monitoring Other Men or Machines

A great deal of research evidence (both experimental and field observational) collected by North American and British researchers shows that man is a poor monitor of infrequently occurring events as well as frequently

occurring events over a long period of time (16). Man becomes distracted or just bored. The evidence is so overwhelming that Fitts, et. al (6) have declared that machines should monitor humans rather than vice versa. This principle has important implications for the design of semi-automatic equipment, as will be discussed in the next major heading. A corollary to the above principle is that man should not be the sole check on the accuracy of his work.

4.4.2.4 Responding Quickly to Control Signals

Machines have microsecond lags, whereas the shortest which can be expected from man is about 200 milliseconds, and this only if he is set to make a movement upon the receipt of a Go/No-Go signal. If a decision is required, the human response time increases rapidly. Moreover, man becomes fatigued rapidly under conditions requiring a series of rapid decisions. Speed, then, is one of the primary qualities of machines.

4.4.2.5 Storing and Recalling Large Amounts of Precise Data for Short Periods of Time

Especially in the computer field, there are requirements for short-term storage of information ("scratch pad" data), followed by complete erasure of the data in preparation for another task. Machines excel at this; humans not only have difficulty memorizing large amounts of information, but their recall is often spotty and they have difficulty in completely erasing information in short-term storage.

4.4.2.6 Computing Ability

People make errors even in the simplest conversions of data requiring no more than simple arithmetic. They are poor at quickly performing highly complex calculations. Such calculations as higher order integrations pertinent to some types of navigation and fire control computations, are beyond the capability of humans. However, machines are limited by the rules of operation that are built into them. In some cases, humans can arrive at an adequate answer more quickly by a series of approximations that drop out unnecessary precision.

4.4.2.7 Handling of Highly Complex Operations (i.e., Doing Many Different Things at Once)

Fitts, et al (6) states that when man has to employ his highest intellectual abilities, he is essentially a one-channel computer -- he can work effectively at solving only one problem or attending to one thing at a time. Only

when he achieves very high degrees of skill can he work on more than one thing, and then only by rapidly shifting back and forth. The machine, however, is limited only by the capacity built into it.

4.4.2.8 Deductive Logical Ability

Machines are much quicker and more reliable than humans in identifying a specific item as belonging to a large inclusive class and in using rules for processing information. If an operation can be programmed 100%, then a machine can be built to perform the operation rapidly and accurately with perfect repeatability. However -- and this is often overlooked -- procedures can be built to enable a human to follow the rules efficiently, though less rapidly, and with a small probability of error.

4.4.2.9 Performance of Routine, Repetitive, Precise Tasks

Man is notoriously prone to commission of errors in such operations. As in monitoring tasks, he becomes easily distracted or he may perform some non-prescribed action out of sheer boredom. However, if the task is sufficiently repetitive that it can become automated, then the operator's involvement in and awareness of what he is doing can be reduced to a minimum and he is free to think of other things. This is one explanation for the compatibility of many persons to extremely routine assembly-line work. In most operating and maintenance tasks on board FBM submarines, this high degree of repetitiveness and restriction in work assignment is seldom to be found. Consequently, it is a safe generalization that machines are superior to humans in the performance of most routine, highly repetitive, and precise tasks.

4.4.2.10 Exerting Large Amounts of Force Smoothly and Precisely

The human is no match in strength for even the simplest lifting or moving devices, and his control movements with large objects tend to be erratic and subject to oscillation, especially when the emphasis is on speed.

II. MAN-MACHINE INTEGRATION

The preceding Part I of this section has presented a detailed discussion of the factors which influence man-machine integration, more or less in order of their occurrence in the system development cycle. In Part II, techniques and guidelines for man-machine integration will be presented.

1 System Models as Aids to Task Assignment

The first step in any man-machine integration analysis is to describe the system under consideration in functional terms. These descriptions are generally referred to as system models or paradigms. Following is a discussion of system models which have been found to be useful in man-machine integration.

1.1 Types of Models

A "system model" is nothing more than an operational description of a system, to be used for analytical purposes. There are many kinds of operational descriptions which can be employed, ranging from the pure verbal description to the pure mathematical or symbolic description as listed in Table 2-7. Depending upon the intended use, some may be more appropriate than others.

Most of these techniques are well known to systems engineers and analysts, and most of them can be quite useful at various stages in system design. However, because of its importance from the human factors analysis standpoint and the success in applying it to the FBM system, the Operational Sequence Diagram (OSD) has been selected for descriptive emphasis in this section. Information on the other methods may be found in any text on systems engineering.

1.2 The Operational Sequence Diagram

During the past few years, a tool for the analysis of man-machine systems has been developed and refined. This tool, called the Operational Sequence Diagram (OSD) and described in detail by Kurke (11), is derived from methods engineering techniques such as the various types of operational process charts described by Barnes (1), Mundell (18), and Maynard and Stegmerten (15). These techniques have been supplemented by the recent PERT-charting concepts and by human factors concepts such as task analysis (17), in which those discriminations, decisions, and actions necessary and sufficient to operate a mechanism are enumerated.

Table 2-7
Techniques of System Operational Description

Type of Model	Description
Verbal Account	
. Scenario	Verbal account of operating procedures, events, timing, etc.
Graphic Representation	
. Block Diagram	Verbal-symbolic account of static connectivity of major system elements. Usually identifies important system variables and their general relationships. Useful also for describing system organization.
. Flow Diagram	Verbal-symbolic account of flow of material or information throughout system.
. Time-Line Chart	Verbal-symbolic representation of critical activities performed by system elements showing time relationships and durations (e.g., Gantt chart).
. Link Chart	Verbal-schematic representation of workspace layout showing frequency of use of "links" between stations.
. Event-Sequence Chart	Verbal-symbolic representation of system operation in terms of critical events and their connectivity and timing (e.g., PERT Chart).
. Operational Sequence Diagram (OSD)	Verbal-symbolic representation of all system activities, their connectivity and timing, with additional identification of sensing, processing, and actuating requirements. At this level of detail, it is possible to assign functions to man and machine and to determine display and control requirements.
Mathematical Model	
. Servo Theory	Symbolic representation of input/output relationships of groups of elements in a closed-loop continuous control system (see this volume, pg. 83, for example).
. Information Theory	Symbolic representation of input/output relationships of elements in a communication channel (see this volume, pg. 80, for example).
. Queueing Theory	Symbolic representation of input/output relationships of elements which perform an administrative, maintenance, or logistic service (see Volume 2, pg. 230, for example).
. Game Theory	Symbolic representation of relationships between action alternatives and costs or losses.
. Decision Theory	Symbolic representation of rules upon which to base alternative courses of action.
. Mathematical Programming	Symbolic representation of all system activities, their connectivity and timing, with the capability of solving for an optimal program.

The Operational Sequence Diagram pictorially displays information-decision-action sequences that a system or its subsystems follow in completing a mission. As such, it directly parallels the basic man-machine functions of sensing, processing, and actuating. In an introductory paper, Brooks (3) defined OSD's as schematic or information-decision-action flow diagrams and described their use in the dynamic description of man-machine systems. He described it as a convenient tool whereby

> "... system operation can be codified simultaneously with hardware designs. The human engineer can lay out his panels realistically; the project engineer can obtain a better idea of the man-machine relationships for various degrees of automation and can therefore evaluate alternative system designs."

A later, more detailed, paper by Kurke(10) presents a complete exposition of the OSD technique and its applications. We are indebted to him for the following discussion and examples.

The OSD may be used to establish sequence-of-operations requirements between subsystem interfaces at various levels of system analysis. The interfaces may be between machines, between operators, or between machines and operators. Simple or complex systems may be analyzed and the degree of thoroughness of the analysis may be selected for maximum usefulness. A second form of OSD stresses its use as a pictorial adjunct to symbolic logic. In this form the basic sequential OSD is combined with a logical analysis technique (10) to depict the logical result of each of several decision-action sequences. The third use of the OSD combines the technique with various link analysis techniques as described by Channell and Tolcott (5) for evaluating panel layout and the design of workspaces.

The basic components of an OSD are various geometric figures coded to denote the elements of any operational sequence (Fig. 2-6). In its simplest form the OSD consists of "actuation" elements depicted by squares, connected by a "time line" uniting the actions. The communication of information in the broadest sense of the term is indicated by a triangle to represent the transmitting action, i.e, talk, switch closure, etc., and a circle to represent the sensing or reception, i.e., hearing words, visual displays, etc. A semi-circle denotes the utilization of stored information such as previously obtained knowledge or training.

When actions and communications are present, the next level of complexity involves the use of the element (hexagon) representing the processing or decision function. Processing may be defined operationally as the variable intervening between a matrix of stimuli and a matrix of possible responses. It is

the raison d'etre for the OSD. The "operator" (which may or may not be human) requires information which is somehow integrated and elicits one of alternative actions or transmissions. As noted in Fig. 2-6, the resultant actions, inactions, or inappropriate actions can be coded in the OSD. Two additional types of symbol are useful at this level of system complexity. One of these discriminates between manual and automatic functions. The other type is a logic device.

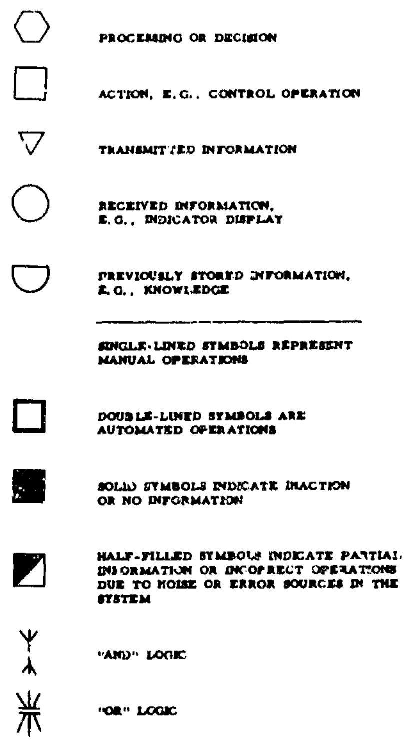


Fig. 2-6. Symbols used in operator sequence diagrams.

Manual elements such as those involving a man driving an auto, seeing a red light, deciding to stop, stepping on the brake, or blowing his horn at a pedestrian are represented by single-lined symbols. The brake light on his car is an example of automatically transmitted information. Automatic elements are depicted by double-lined squares, triangles, etc. For instance, the brake light of the car going on would be depicted by a double-lined circle. The second type of symbol is logical in nature; it discriminates between logic conjunctions. Separate time lines entering or leaving an element represent an "or" condition.

"And" is represented by the junction of two lines prior to entering, or subsequent to leaving the element.

Operational Sequence Diagrams may be used during various phases of system development from the initial determination of the sequence of gross operations to the detailed evaluation of panel layouts. To illustrate its use on an unclassified basis, let us examine how it might be used in the development of Campbell and Blank's proposal for a shipboard radar data computer to improve navigation safety by reducing the likelihood of ship collisions.(4) Such a collision avoidance system consists of a ship and an environment which contains objects to be avoided. To accomplish its mission, the ship must meet the following requirements. It needs:

- Knowledge of potential collision objects in the environment.
- Knowledge of own status relative to objects in the environment.
- Capability of determining CPA (closest point of approach) and, from this, deciding whether to evade the object.
- Ability to take actions necessary for evasion from a universe of acceptable evasive tactics.
- Feedback for evaluation of usefulness of evasive tactic.

Assembling the required navigation functions in a sequential order, the mission can be generalized as illustrated by the sequential OSD in Fig. 2-7, in which information concerning navigation hazards such as another ship is received by the collision avoidance system. This information, knowledge of own ship's heading, speed, etc. and of those actions permitted by the rules of the nautical road are all utilized in the decision to change own ship's course. A new course is chosen and plotted and the ship is put on the new course. The new relative bearing and speed of the other ship is received and the decision concerning the adequacy of the new situation is evaluated to determine the effectiveness of the maneuver.

The first step in analyzing the system is to compare the human factors elements in the existing system and in a proposed system. An examination of the allocated man-machine functions can be made to yield comparative data on the human error potential of both systems.

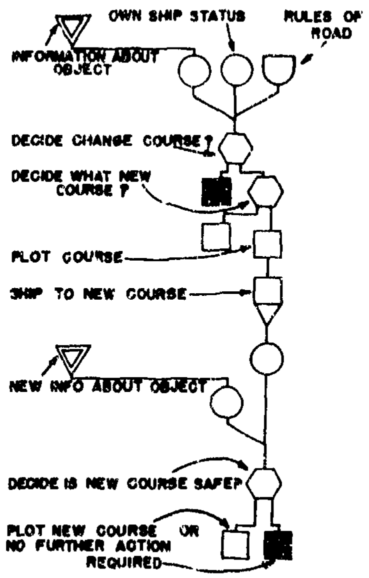


Fig. 2-7. Basic collision avoidance system

The very question of the desirability of the hypothetical radar computer is one of allocation of man-machine functions. In effect, the development of the radar computer would produce a new system and the relative effectiveness of the two systems should be compared. A very satisfactory method of determining the effectiveness of alternate systems is the comparison of OSD's representing them. More detailed diagrams than the one in Fig. 2-7 are needed. In addition to the ship and its environment, we are now concerned with the watch officer and the radar computer and in the detailed interactions of these components.

Fig. 2-8 illustrates this level of analysis of the conventional system and the proposed system incorporating a radar data computer.

The manual system (Fig. 2-8A) requires that a target be identified, and if a casual estimate indicates it might be a threat, its course relative to own ship is plotted to determine if the two ships are on a collision course. An evaluation of the plotted course is made and if the decision to maneuver to avoid the other ship is made, a new course is plotted. Then own ship is put on a new speed and heading. Subsequent to this change, the relative course of the other ship is replotted and the collision threat is re-evaluated.

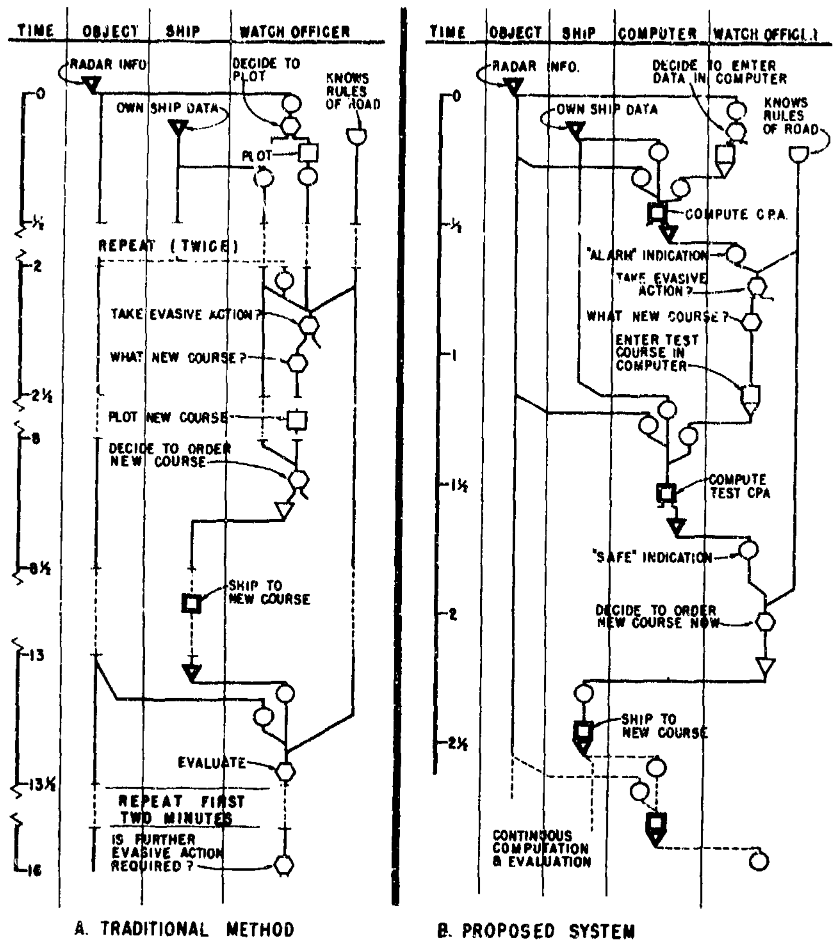


Fig. 2-8. Detail analysis of alternate collision avoidance systems

The computer system (Fig. 2-8B) also requires that a target be recognized and identified. The target is then entered into the computer, which continuously evaluates the relative threat. When the evaluation indicates a collision course, an alarm notifies the watch officer, who -- on the basis of computer-fed displays -- identifies which of several targets represents the collision threat.

The watch officer simply estimates a change of course and/or speed and enters this change in the computer, which evaluates it. If the threat is eliminated, the alarm and threat indications are replaced by an "OK" display. The watch officer now simply orders the change in speed and heading he previously had entered into the computer. This entire sequence can be completed in a fraction of the time required for the manual sequence. In addition to illustrating elapsed time graphically, a time scale on the OSD shows the input and output rate load imposed on the human operators in the system.

A comparison of the operations involved in both systems indicates that the types of error leading to collision potential are less easily designed out of the original system than the one with the computer, i. e., provided a correct entry is made, computation of CPA is less subject to error and more rapidly performed by electronic than by human computers.

In general, when the sequence reaches a major decision point, the practice is to prepare separate OSD's for each alternate action. If a system requires numerous decisions, this practice could result in more diagrams than can be handled conveniently. To overcome this disadvantage, computer programming techniques are incorporated into the OSD to show the effects of alternate actions on a single diagram. To illustrate the logical analysis form of the OSD, the watch officer in our hypothetical collision avoidance system makes decision F, the choice of a course (Fig. 2-9). Two alternatives, G and H, are shown. If he enters course G into the computer, data from the other ship via radar K and data concerning own ship L are integrated and computed. If conditions indicate that the entered alternate would lead to another collision course, it would be so indicated by the computer's display R and a series of decisions (S, V) must be made by the watch officer to choose another course. If the alternative course H is chosen, this entry (with inputs K and L) will cause the indications P and Q that the entered course has a safe CPA. The watch officer uses this information in his decision S to order T, a change in the ship's course.

This use of the sequence diagram suggests its use with a system of symbolic logic. The results of the alternate decisions shown in Fig. 2-9 may be written as a series of logical sequences, thus:

$$A_i \cdot B_i \longrightarrow C_i \longrightarrow [(D_i \cdot F_o) \longrightarrow E_i] + (D_o \cdot F_i) \qquad (1)$$

$$F_i \longrightarrow [(G_i \longrightarrow I_i) \cdot H_o] + [G_o \cdot (H_i \longrightarrow J_i)] \longrightarrow \overline{M} \qquad (2)$$

$$K_i \cdot L_i \cdot (I_i + J_i) \longrightarrow M_i \qquad (3)$$

$$\begin{aligned}(H_i \longrightarrow J_i) \cdot K_i \cdot L_i \longrightarrow M_a \longrightarrow (N_i \cdot O_o) \\ \longrightarrow (P_o \cdot Q_i) \longrightarrow S_a \longrightarrow T_i \longrightarrow U_i\end{aligned} \qquad (4)$$

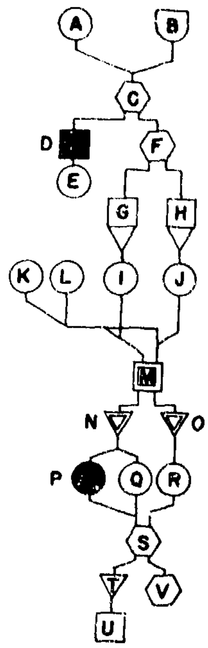


Fig. 2-9. Analysis of alternate actions

$$(G_i \longrightarrow I_i) \cdot K_i \cdot L_i \longrightarrow M_b \longrightarrow (N_o \cdot O_i) \longrightarrow R_i \longrightarrow S_b \longrightarrow V_i \qquad (5)$$

where the capital letters stand for the elements in the OSD; small o used as a subscript represents the null state of the element; i is used to denote an only active state, and a, b, c, ..., etc., are used as subscripts when an element has more than one active output; a dot indicates <u>and</u> logic; and a plus indicates <u>or</u> logic. The bar over the capital letter means that the element indicated receives only part of its requisite inputs in this sequence. It indicates that other inputs to the element are necessary to change it from the null to the active state.

The ability to reduce graphic representation to the notation of symbolic logic enables the analyst to use the latter methodology in establishing meaningful operational procedures. This graphic-logical translation also provides a method for evaluating the relative effectiveness of various combinations of manned and automated system components.

In addition to its uses in system analysis and design, the Operational Sequence Diagram has a role in the design and evaluation of equipment. One method requires the development of very detailed OSD's showing on a time scale the inputs and outputs required by the operator for his information-decision-action sequences. These inputs and outputs may come from other equipment or from other personnel in the system. The time of input and output information becomes one of the contributing factors in the design of equipment. The OSD used as a method for studying interpersonal communications required by the system can be used in the determination of the number and location of operating personnel.

Operational Sequence Diagrams may be laid out spatially as well as along a time line. The spatial layout method overlays the inputs and outputs to the operator on a sketch of the panel face. Fig. 2-10 illustrates this technique in the comparison of two panel designs submitted for a given sequence. Both panels consist of two toggles and six indicator lamps. The sequence of operations commences at the arrow and is shown by the line connecting three types of OSD elements: squares, standing for switch operations; circles for indicators on; and spots for indicators off. The spatial layout form of OSD provides a graphic description of the perceptual-motor load a particular layout imposes upon the decision-making function of the equipment operator.

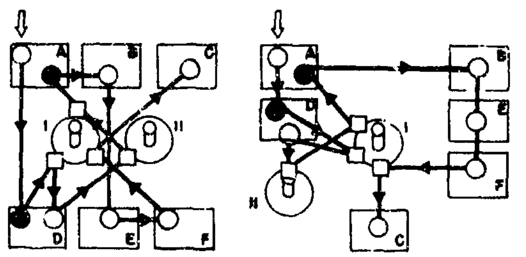


Fig. 2-10. Spatial OSD superimposed on two panel layouts

However, perhaps the most important end product of this method of analysis in any of its forms is that the information and action symbols on an OSD can be utilized directly to determine display, control, and programming requirements, from whence man-machine interface design may proceed.

In summary, the Operational Sequence Diagram is a type of process chart modified for the peculiar needs of human factors work. Its primary use

in the FBM system has been in determining man-machine interaction sequences in the Mk 80 and 84 Fire Control and in the Launcher systems, in analyzing information flow requirements between groups of men and machines on the FBM submarines, and in coordinating information-decision-action sequences between interfacing subsystems. Since these sequences relate directly to the sensing-processing-actuating functional capabilities of man and machine, they can be used to determine display, control, and programming requirements.

2 Man-Machine Task Assignment Guidelines

System requirements seldom require the selection of the best components for the system; instead, one usually wants to know what available components will adequately meet system requirements so that the least expensive or the most readily available components which meet the requirements may be used. If man is viewed as any other system component, he may be selected to perform a given function even though he may not perform the function as well as a machine, provided that his performance still meets system requirements. Thus, a task may be assigned to man if he is already available to perform it and if this involves less cost than using hardware. In still other instances, there may be no choice in the assignment of tasks; either they must be performed by man or they must be performed by machine. For example, the computations required for the missile guidance are too complicated and must be updated too frequently to be performed by man. On the other hand, selection of programs for NAVDAC or the selection of pass time for TRANSIT fixes must be performed by man. Also, in a somewhat different category, there is the performance of back-up operations. Man is frequently used to perform manual operations when more automatic modes of operation are not possible because of their inappropriateness or because of equipment malfunctions.

In viewing man as a potential system component, the implication is that human performance capabilities and limitations can be specified in the same manner as any hardware component within the system. However, the performance characteristics of man cannot be specified precisely for many of the functions which man can perform. For some sensing functions, such as vision and hearing, human characteristics can be specified quite accurately. Similarly, actuating capabilities and limitations are fairly well known. However, for processing functions such as reasoning and decision making, human characteristics can, with few exceptions, be specified only in the most general of terms. Also, because of man's adaptive capabilities, his characteristics must often be specified in terms of the range of task or input conditions over which he can perform effectively.

In the following guidelines for assignment of sensing, processing, and actuating functions, main emphasis has been placed upon the processing functions for three reasons:

. Sensing and actuating characteristics of the man as opposed to the machine are well documented in other handbooks and available references and have been utilized in developing the guidelines for selection and design of equipment and components in Volume 2 of this handbook.

. The trend in modern Naval weapon systems, as exemplified by the FBM system, is toward increasing automation of processing functions.

. A knowledge of human processing characteristics is important in early system development when relative roles of man and machine are being established.

For these reasons, a detailed discussion of human processing characteristics is included herein, whereas human sensing and actuating characteristics are only briefly summarized.

2.1 Sensing

In deciding whether equipment or personnel should perform specific functions related to receiving inputs, information is needed about:

. the requirements for energy detection and distrimination; and

. the system- and use-determined factors influencing energy detection and discrimination.

Energy detection and discrimination refers to the ability to receive or sense electromagnetic, particulate, and/or mechanical energy without specific regard to signal qualities or informational content. Detection refers specifically to the absolute presence or absence of physical energy, while discrimination refers specifically to the presence or absence of a difference between physical energy levels. The reception of these energies requires the presence of a sensing mechanism which can be affected by the particular type, range, magnitude, and other qualities of the energy. Obviously, both man and equipment are capable of receiving many forms of physical energy. This detection or reception by the senses is prerequisite to discrimination and later processing. System- or use-determined factors may then dictate other uses of equipment or personnel for sensing and may require compromises in the assignment of tasks. In one instance, though limited in detection and discrimination capabilities as compared with a specific equipment sensor, man may be required in the system because of his multipotentialty for sensing many forms of physical energy. In other instances, where detection would be monotonous, hazardous,

inefficient, or impossible for man to perform, equipment sensors may be required or desirable. The guidelines which follow serve to structure the man-machine assignment decision with respect to the critical function of sensing.

2.1.1 Detection and Discrimination

* Detection and discrimination of specific physical energies should be performed by equipment sensors, except for the following considerations:

  a. If the situation requires the reception of many different types of physical energy in close proximity in time but not simultaneously (such as might be involved in steering a vehicle, where visual, auditory, tactual, and kinesthetic sensing all may be useful for control), the multipotentiality of man's senses may indicate his use for detection and discrimination functions.

  b. If high noise levels are present, it may be necessary to utilize man to detect signals. This capability is often associated with detection of signals on cathode-ray tube displays and use of communication equipment.

  c. If equipment sensors cannot be designed to provide effective scanning, then it may be necessary to use man. Man, through his ability to direct his attention to various portions of his environment, may provide a more effective means of detection than more highly programmed equipment sensors.

  d. If contingencies which may arise in the operation and maintenance of the system cannot be predicted adequately during its design, it may be necessary to include man as a sensor for some back-up functions.

  e. If effective equipment sensors cannot be designed, then it may be necessary to use man. For example, man must be included to detect visual signals associated with the use of radar equipment, auditory signals associated with the use of sonar, and wave forms associated with the use of test oscilloscopes. This may, in some instances, involve the

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The * symbol indicates specific guidelines for the allocation of functions.

detection of low-energy levels which might fail to activate an equipment sensor.

f. If man is already present in a given situation, it may be more economical to use him as a sensor than to provide additional equipment if the sensing requirements are within the range of human sensitivity. This also is related to the desirability of providing a man with enough work so that he will maintain a reasonable level of motivation and alertness.

2.1.2 Conditions for Employment of Personnel for Detection and Discrimination

* If personnel are used to perform energy detection and discrimination functions, then the dynamic range, intensities, and frequencies of the energy inputs should be within the capabilities of the human senses.

a. Since the effective utilization of man as a sensor (such as might be required under the conditions described in the preceding guideline) is constrained by the sensitivities of the human senses, it is necessary to describe some of their capabilities and limitations. The physical variables associated with stimulation of the human senses are generally defined in terms of (1) type, (2) intensity, and (3) spectral or frequency distribution. The characteristics of the sensory receptors in responding to the physical stimuli may be defined in terms of dynamic range, amplitude resolution, spectral range, spectral resolution, spatial resolution, and temporal resolution (i. e., acuity).

b. One important characteristic of human sense organs is their ability to change their sensitivity as a result of recent or on-going stimulation. This characteristic is called sensory adaptation. A commonly experienced example, visual dark adaptation, results in an increased sensitivity to achromatic light following a relatively short initial period in darkness. On the other hand, exposure to daylight conditions results in reduced sensitivity to low-level light sources or signals. Practical application of this phenomenon traditionally has been made in ship control stations (low-level red light), aircraft cockpit illumination (also low-level red light) for night flying, and in radar control

rooms, where observation must be made of low-level visual stimuli.

The important relevant sensory limitations are summarized in Table 2-8. Details concerning each sensory mode are included in appropriate sections of Volume 2, Design of Equipment, and are presented therein in terms of specific design requirements for display design and environmental control.

2.1.3 Monitoring

* Long-term monitoring of specific physical energies generally should be performed by equipment sensors.

In addition to his unsuitability for the detection of electromechanical energies per se, man is typically a poor monitor of infrequently occurring events or events occurring over long periods of time. He is easily distracted and he may become bored or fatigued. Again, as with detection, there may be conditions which require the use of man for monitoring in spite of these limitations. Thus:

a. If signals must be detected in high noise environments, then it may be desirable to use man for monitoring. In operational situations, this applies mostly to cathode-ray tube displays such as radar displays, auditory equipment associated with sonar, and external communications equipment. In maintenance situations, this capability is most relevant in the use of test oscilloscopes.

b. If the unpredictability of the signal makes it difficult or impossible to use an equipment sensor, then it may be necessary to use man. For example, the visual and auditory capabilities of man may be useful when it cannot be predicted:

   (1) Where the signal will occur, although some notion may be had of when it will occur;

   (2) When the time of onset will be, although the position in space of the signal is predictable;

   (3) Whether something is going to occur.

   Again, these involve the multipotential capabilities of man's senses where the complexity or the unpredictability of the input situation makes it difficult or impossible to use equipment sensors.

Table 2-8

SUMMARY OF HUMAN SENSORY LIMITATIONS RELEVANT TO EQUIPMENT DESIGN[1]

Parameter	Vision	Audition	Touch and Mechanical Vibration	Kinesthesis
I. Receptor	Eye	Ear	Skin and underlying tissue	Muscle and tendon nerve endings; joints,
II. Nature of Stimulus	Some electro-magnetic waves	Some amplitude and frequency variations of pressure in surrounding media	Amplitude and frequency variations of pressure causing tissue deformation	Muscle stretching and contraction; sub-cutaneous pressure
III. Frequency or Spectral Discrimination				
A. Range				
1. Maximum	300-1050 mu (4)	20-20, 000 cps (2, 3, 4)	1-10, 000 cps (4)	Not Applicable (NA)
2. Optimal	400-800 mu (2)	200-10, 000 cps (7)	Not Reported (NR)	NA
B. Resolution				
1. No. of JND's				
a. No. of Relative DL's	~ 128 @ Medium Intensities (4)	1800 (20-20, 000 cps @ 60 db) (3)	180 (1-320 cps)(4)	NA
b. No. of Absolute DL's	~ 10 (Brightness >1mL)(3)	4-5 (3)	NR	NA
2. Size of JND	1-5 mu (450-650 mu)(2)	2-5 cps (30-2000 cps)(3, 7) [$\Delta f/f \cong .005$(500-800 cps)(2)]	~25 cps (7)	NA
IV. Intensity Discrimination				
A. Range				
1. Maximum	100 db (.000001-16, 000 mL)(2, 5)	~0-130db (4, 5) (0db=.0002 dynes/cm^2)	3-300g/mm^2 (for Finger Tip) [>300=Pain] (2)	Min: .3° @ .3° sec. (passive joint movement)(6) Max. - NR
2. Optimal	1-100 Ft. -Candles (Depending on Task) (1, 3)	40-70db @ 2000 cps (3)	NR	NR
B. Resolution				
1. No. of JND's				
a. No. of Relative DL's	~570 w/White Light (4)	325 @ 2000 cps (4)	15 (in Chest Region) (.05-.5mm Amplitude)(4)	NR
b. No of Absolute DL's	3-5 (0.1-50 mL White Light)(4)	~3-5 w/ Pure Tones	3-5 (4)	NR

2. Size of JND	$\Delta I/I \cong .01-.02$ (@ High Illumination Levels)(7)	$\Delta I/I \cong .09$ (1000 cps @ 100db) (7)	$\Delta I/I \cong .14$ ($5g/mm^2$)(7)	$\Delta I/I \cong .08-.12$(6)
V. Spatial Discrimination	A. Perceptible ~0.5 [1, 2 / 3, 5] B. Separable ~1 min (2)	~12° (Average error of Localization in Horizontal Plane) (2, 7)	4-5mm (Hand) (2)	NA
VI. Temporal Discrimination	CFF=20-50 cps (2, 5, 7)	~2.5 ms (7)	~20/sec (Separate touches sensed as discrete) (5)	NR
VII. Simple Reaction Time	~.20sec (2, 3, 7)	~.16 sec(2, 3, 7)	~.17 sec. (2, 3, 7)	~.15 (5, 6)
VIII Indications for use	1. Spatial orientation required 2. Spatial scanning or search required 3. Simultaneous com parisons required 4. Multidimensional material presented 5. High ambient noise levels	1. Warning or emergency signals 2. Interruption of attention required 3. Small temporal relations important 4. Poor ambient lighting 5. High vibration or G forces present 6. Confirming or warning feedback on system operation required via alternate (non-visual)mode	1. Conditions unfavorable for both vision and audition 2. Visual and auditory senses disabled 3. Confirming or warning feedback on system operation required via alternate mode	1. No method yet exists for directly utilizing this sensory mode 2. Confirming or warning feedback on system operation required via alternate mode

1. The sources quoted provide the most representative data selected from among the references listed:

1. Chapanis A., Garner, W. R., and Morgan, C. T. Applied Experimental Psychology. Wiley: New York, 1949
2. Handbook of Human Engineering Data. Second Edition (Rev.) Tufts College, Institute for Applied Experimental Psychology, 1952.
3. Morgan, C. T., et. al. Human Engineering Guide to Equipment Design. McGraw-Hill: New York, 1963.
4. Mowbray, G. H. and Gebhard, J. W. Man's Senses as Information Channels. In: Selected Papers on Human Factors in the Design and use of Control Systems. Sinaiko, H. W. (ed.), Dover Publications, New York, 1961.
5. Stevens, S. S. (ed.), Handbook of Experimental Psychology. Wiley: New York, 1951.
6. Wenger, M. A.; Jones, F. N., and Jones, M. H. Physiological Psychology. Holt: New York, 1956.
7. Woodworth, R. S. and Schlosberg, H., Experimental Psychology. Holt: New York, 1956.

c. If equipment cannot be designed to handle monitoring requirements, then it may be necessary to use man.

d. If man is already present in a given situation, it may be more economical to use him as a monitor than to provide additional equipment, provided the monitoring tasks are properly designed to compensate for man's limited capabilities.

2.1.4 Conditions for Employment of Personnel for Monitoring Functions

* If man must be used to perform monitoring functions, then his limitations for monitoring must be considered.

There is considerable evidence, based on investigations of watch keeping and inspection work, which indicates that the ability to detect and respond to small unpredictable signals varies with the passage of time(14). In general, the efficiency of vigilance rises rapidly at the start of the monitoring period and decreases rapidly again when the period lasts longer than half an hour. This general and universal finding, taken together with other experimental results, leads to the careful consideration of the following factors in designing human monitoring tasks.

a. Signal Characteristics

(1) Personnel are more likely to notice frequently recurring signals than those occurring less frequently.

(2) Regularly spaced signals are more easily and more reliably detected than irregularly spaced signals.

(3) Time lapses between one signal of interest and the next appear to be of very great importance.

(4) The longer the working span (i.e., the watch-keeping situation), the more decrement in vigilance can be expected. However, short rest periods apparently restore some response readiness, although the data do not suggest the optimum length of the rest periods.

(5) It has been suggested that the regular repetition of unwanted signals (i.e., signals of no interest) might be just as harmful for alertness as the irregularity of signals of interest.

b. Environmental Characteristics

(1) Personnel isolation reduces alertness. Research has shown that isolated subjects are less alert than those working with somebody else. At the same time, elimination of distracting conditions also seems to lead to a decline in readiness to detect and respond to small changes in the environment.

(2) Moderately noisy and uncomfortable surroundings seem to increase watchfulness. The implication here is that some minimum sensory stimulation is necessary to maintain vigilance.

c. Motivational Characteristics

(1) Motivation can be increased by providing immediate knowledge of results during the task so that personnel are given some basis for judging their own performance.

(2) Personnel can get tired of sitting still and receiving information. It has been said in this regard that personnel also show fatigue who only sit and watch.

(3) Tasks with a strong perceptual element (e.g., maintaining a pointer on a stationary mark) are particularly likely to show bad effects from prolonged work.

(4) Monotonous surroundings contribute to decrements in vigilance.

(5) Human vigilance may be aided by self-pacing as opposed to machine pacing of monitoring tasks.

d. Implications

System design should allow for human vigilance variables in any task situation and should attempt to minimize vigilance decrement by three important steps:

(1) Infrequent signals should be presented regularly and should have strong behavioral coding. In this regard, color, position, movement, use of multiple senses, and various other

coding schemes should be utilized to enhance the attractability, detectability, and meaningfulness of the signal.

(2) The task situation should provide personnel with immediate knowledge of results (i.e., feedback) so as to impart to them a complete experience and a basis for improving performance (see pg. 85, this volume, for detailed discussion).

(3) Control must be exercised over the signal environment such that stress situations are avoided and minimal sensory stimulation is afforded to personnel. In this regard, the regular occurrence of unwanted signals should be minimized.

2.2 Processing

The preceding section has been concerned with the simple detection and discrimination of physical energies and the continued detection of these energies over extended periods of time (i.e., monitoring). In this section, guidelines and considerations are provided on the capabilities of personnel and equipment to interpret, store, retrieve, associate, integrate, and otherwise process information. An analysis of the man-machine assignment problem with respect to information processing requires consideration of: 1) the types of processing; 2) the capacities; and 3) the factors which influence this processing. Each of these will be discussed in the following sections. While the term "information processing" refers broadly to an entire input-output or stimulus-response complex, it may also be categorized in terms of the nature and degree of input/output integrating activities involved. From this viewpoint, information processing may be classified into the following types:

- Where the operation is essentially that of a relay or amplifier (i.e., a more or less direct stimulus-response or input/output connection). Examples of human processing activities of this nature would be the task of operating a push button when a light comes on and a simple position tracking task.

- Where the operation is one of encoding. Here there is a transformation of the input signals such that the response or output may be qualitatively and/or quantitatively different from the input. The tasks of translation, of keying a code number to represent address information, and of binary-to-octal transformation are good examples.

.. Where the operation is one of evaluating and/or decision making. This is a response- or output-selection-type of situation in which risks, values, or utilities are assigned to alternative actions or responses; and responses, when made, are thus based upon a weighting of the input information and take the form of a selection from among alternative outputs.

Following are guidelines for assignment of processing functions to man and machine, together with a discussion of the factors which influence this assignment.

2.2.1 Interpretation

* Interpretation of complex physical energy inputs should be performed by personnel.

  a. Interpretation, as used herein, refers to the capacity to recognize or ascribe meaning, contextual relations, or organization to sensed energy. As such, it represents a first level of processing. Of course, any equipment transformation involving transducing, filtering, or amplification functions can be thought of as interpretation in the sense of simple processing of signals. However, the concern here is with situations which involve more complex signal transformation and organization.

  b. Because of his capabilities for attending to selected portions of his environment, detecting many forms of physical energy, ascribing meaning to them based on past experience, and responding with appropriate actions, man is more effective than equipment in many situations where transformation of inputs is required. This is most evident in the perception of patterns and recognition of these patterns in new or unusual stimulus situations. For example, this includes the capabilities of man to interpret wave forms on cathode ray tube displays, interpret radar and sonar displays, etc. Examples of how this perception of patterns or relationships can be transferred from one situation to another are evidenced in man's ability to steer vehicles under varying environmental conditions.

  c. Some limitations of human interpretive abilities should be noted:

(1) Past perceptual experiences influence present interpretation and, conversely, current interpretive activities influence stored events and change them both qualitatively and quantitatively.

(2) The reliability and content of signal interpretation is particularly susceptible to emotional and intellectual errors (both constant and sporadic), as well as physical degradation (decreased sensitivity because of sensory fatigue, etc.). This problem of attaining and maintaining reliable and valid human interpretation of physical energy can be mitigated by adequate design engineering (e. g., information displays), personnel training (including practice and training support documents and materials), and on-the-job proficiency reinforcements, training and proficiency exercises, etc.

2.2.2 Generalized Processing

* Generalized information processing and decision making should be performed by personnel where:

  a. Pattern perception is important (especially where patterns may change in size, position, or energy configuration (types and strength levels) under different conditions.

  b. Long-term storage of information is required.

  c. Insight, discovery, or heuristic problem solving is required.

  d. Decision making and learning in a complex changing situation are required.

  e. Ability to improvise and adopt flexible procedures is important and, within the state of the art, cannot be built into a machine program.

  f. Number of low-probability events which might occur is high and the cost or capacity of machine programming is exceeded by the requirement.

  g. Inductive reasoning is required, i. e., a requirement exists for generalizations to be made from the specific events.

2.2.3 Specialized Processing

* Specialized information processing and decision making should be performed by equipment where:

  a. Deductive logic can be programmed.

  b. Speed and amount of memory search or entry (storage) is an extensive requirement.

  c. Highly complex computations or logical operations are involved.

  d. Short-term storage and retrieval of large amounts of data is required.

  e. System functioning requires extremely short time lags between scheduled events.

  f. Many routines, channels, and memory areas must be utilized simultaneously (parallel operation).

  g. A high degree of repetitiveness and routine is involved in the sequence of tasks or events.

  h. Events are unambiguous and probable but can be expected to occur only infrequently, e.g., as in monitoring of equipment readiness.

  i. Reduction of the over-all amount of work load and activity for personnel can be expected and provided within system cost parameters.

2.2.4 Short-Term Storage and Retrieval

* Storage of large amounts of data and recall for short periods of time should be performed by equipment when:

  a. Information is low in meaningfulness to the human, even though it may ultimately be useful to him.

  b. Encoding or identification for library search can be simpler than the symbolic processes utilized by humans for the purpose of recall.

c. Rapidly committing large amounts of information to storage is required, since humans often cannot recall information and apparently cannot completely erase learned material -- a factor which sometimes creates considerable unreliability and lack of validity in operator performance.

2.2.5 Long-Term Storage and Retrieval

* Long-term storage and recall of meaningful material of considerable contextual complexity should be performed by personnel when:

a. Retention of abstract and symbolic material and its selective recall for a wide variety of applications is required.

b. Modification of retained material in the direction of new learning about a constantly changing environment is required.

c. Judgment in situations is required where all the relevant factors cannot be clearly specified in advance.

d. Self-modifying behavior based upon retention of experienced events is required.

2.2.6 Conditions for Employment of Personnel for Processing Functions

* If personnel are used to perform information processing functions, then the information characteristics, rate, storage, and retrieval requirements must lie within human capabilities.

There are many system- and use-determined factors which affect human information processing. Anything which affects behavior will, in a broad sense, affect the information-processing performance of the human. This includes the compatibility of the stimulus-response situation, the speed, regularity, and other conditions of stimulus presentation, the skill of the human, the effects of practice, the effects of noise and irrelevant information, and the nature of feedback or knowledge of results. (These factors are not mutually exclusive.) These factors are discussed below under five major headings: Input/Output Characteristics; Storage and Retrieval Characteristics; Capacity; Transfer Function; and Feedback.

a. Input/Output Characteristics

(1) Reaction Time

The majority of personnel tasks in the FBM system involve reactions to discrete signals. These reactions can be simple or complex, depending upon whether or not the personnel have to make decisions about the signals to which they will respond.

(a) Sensory Mode

. For the three senses most likely to be used (auditory, visual, and tactual), the differences in time lags are small and probably insignificant for most, if not all, applications. The following data are typical of reaction times obtained in studies of human responses to simple stimuli impinging upon the various sense modalities:

Touch	0.115 - 0.190 sec
Hearing	0.120 - 0.432 sec
Vision	0.160 - 0.476 sec
Vestibular (sense of balance)	0.190 - 1.450 sec
Kinesthesis (muscle sense)	0.240 - 0.350 sec

. Odor and pain, which are physiological warning devices, have long reaction times.

. Reaction time for combined signals (signals going to two or more senses simultaneously) is no shorter than for the one signal giving the fastest reaction time.

. Implications: The value obtained from selecting the sense to be used solely on the basis of reaction time is small; other design considerations are nearly always more important. For example, auditory signals are poor when the ambient noise level is high; visual signals are poor when they may appear outside the normal viewing area of the operator.

(b) Signal Characteristics

. The larger the size or area of a (visual) signal, the faster will be the reaction time, up to some limiting value.

. The greater the intensity of a signal, the faster will be the reaction time, up to some limiting value.

(c) Signal Duration

. The duration of a signal has very little effect on reaction time provided the signal is easily visible or audible. Very short signals (0.1 second or less) may produce longer reaction times; however, their main disadvantage is the likelihood that they may not be noticed at all.

. Although no general relationships have been established, the quality of certain signals does evoke faster reaction times. For example, high frequency sounds have a slightly faster reaction time than low frequency sounds.

. There is a faster reaction time to visual signals which strike the center rather than the periphery of the eye.

. There is no difference in simple reaction time to flashing or steady signals. However, when one intermittent signal has to be distinguished from a steady one, reaction time is directly related to the flash length of the intermittent signal, because flashing and steady signals are indistinguishable until the flash is ended.

. Implications: Visual signals should be of sufficient size, brightness, and duration to be easily and obviously seen. (Detailed recommendations for their design are presented in Volume 2). Duration should never be less than 0.5 second, and, where applicable, the signal should last until the appropriate response has been made. Nothing is

gained in speed by using a flashing signal rather than a steady one. However, in many applications a flashing signal is preferred to a steady one because of its greater attention-demanding value. Important signals should be placed in front of the operator or as close to this location as possible. Auditory signals should be sufficiently different from the prevailing noise background to be easily and obviously heard. Signal duration should be at least 0.5 second, and, where applicable, the signal should last until the appropriate response has been made.

(d) Signal Complexity

. In some instances the signals which are to be responded to may not be perfectly discriminable (distinguishable) from each other. The act of discrimination takes time; the more difficult the discrimination, the longer the time. Reaction time is a sensitive measure of the observer's uncertainty, so that when he is just barely capable of making a correct judgment, the extra effort is reflected in a longer reaction time.

. As the number of available signals increases, the time required to respond to any one also increases. (See discussion on channel capacity, pg. 79, this volume.)

. There are three important cases when the above statements do not apply:

- When all possible signals are not equally likely to occur. The most likely signals will have the shortest reaction time; the least likely will have the longest.

- When the signals can be grouped in some meaningful way. Reaction time will tend to be proportional to the number of groups rather than to the number of separate signals.

- When the signals are sequentially arranged. Once the operator learns the arrangement,

reaction time will be a function of the number of signals which can occur at the next sequential step.

- Reaction time is generally lengthened more when discriminability is reduced than when the number of signals is increased.

- Implications: The number of signals should be kept to a minimum for the required task; each additional signal will increase the time required to respond to any one. When the signals are not independent, they should be arranged in such a way that the operator can easily see their relationships. Instruments should be so designed and arranged as to facilitate human reception of signals. (Detailed recommendations for instrument design and panel layout are given in Volume 2.)

(2) Stimulus-Response Compatibility

In general, the more compatible the stimulus with the response, the greater the rate of information processing. + Among the relevant considerations for stimulus-response compatibility are the past experiences of the human, population stereotypes (e.g., the OFF position of light switches in England is "up"), the parallelism between the stimulus presentation and the response media, and the nature of the encoding required by the situation. Under certain conditions, for example, verbal responses to visual inputs will result in an information transmission rate greater than manual responses to these same stimuli.

(3) Encoding Requirements

The nature and/or degree of encoding involved in the task is thus an important aspect of stimulus-response compatibility. The easier the encoding requirement, the greater

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+ Stimulus-response compatibility refers to the interaction effects of the nature and mode of stimulus presentation with the nature and mode of the response medium. It essentially determines the amount of enco ing which the man must perform.

will be the rate of information transmission for any set of stimulus alternatives.

(4) Statistical Characteristics

The assignment of response categories on the basis of the statistical properties of the stimulus and response alternatives will improve the rate of information transmission, i. e., the faster and more easily made responses should be paired with the more frequently occurring stimuli. The Morse code is based upon this principle, with the most frequently occurring letter, "e," encoded as the simplest, briefest response, "dot."

(5) Data Presentation Characteristics

The speed, intermittence, and other conditions associated with the presentation of signals to an operator will affect the rate of information processing. Up to a point, increasing the rate of information presentation will increase the rate of information transmission (see discussion on capacity under (8), below) As the time between signals becomes longer and/or more variable, the rate of information processing will decrease and performance will be more variable. If the conditions of data presentation provide partial or complete advance (anticipatory) information about the $(n + 1)^{th}$ input stimulus while the operator is still responding to the n^{th} stimulus, the rate of information transmission will generally be increased.

(6) Self- vs. Machine-Pacing

For tasks which continue for an extended period of time, the average amount of information processed will usually be greater when the operator can control the rate of input signals (self-pacing) as opposed to conditions where the input rate is controlled by external conditions such as machine cycle time (machine-pacing). This occurs because time lost can be regained in a self-paced but not in a machine-paced task.

(7) Skill and Training

With respect to skill level and/or the effects of practice, the rate of information processing will increase up to

some limit as a consequence of practice and/or increased skill. Practice results in greater selectivity in what the human attends to, elimination of unnecessary response components, and an improvement or refinement of necessary response components.

(8) Noise

The presence of "noise" (interference during the presentation of input stimuli) will adversely affect the rate of information processing. Also, the amount of irrelevant material through which the human must search in order to detect or identify the relevant signal will degrade information processing performance. Practice will assist only to a degree in overcoming the effects of noise and irrelevant material.

b. Storage and Retrieval Characteristics

It can be expected that the degree to which any material will be stored will be determined not just by the passage of time, but by such factors as are described below:

(1) Conditions under which the Information is Committed to Storage

(a) The greater the degree of original learning, the better the retention. Overlearning importantly assists human storage.

(b) Practice distributed over the learning period is especially helpful in promoting retention. Distributed practice and rehearsals are generally more effective than massed or highly concentrated sessions, especially for large amounts of complex information.

(c) Material with a high degree of meaning to the human is better retained than less meaningful data such as codes and abstract symbols.

(d) Dissimilar material events are retained better than similar material. Increased similarity, short of identity, between two activities being committed to storage generally will result in increased forgetting.

(e) Long lists or sequences of material to be committed to storage generally produce differential retention; the beginning and end of the material are retained better than the intervening material.

(2) Activities of the Human Before, During, and After Initial Storage of Information

Increasing the amount of additional learning between successive recalls of stored material decreases the retention of that material. Rehearsal of the stored material, however, generally helps retention.

(3) Conditions of Retrieval from Storage (e.g., Recall, Recognition, Reproduction, Relearning)

Information retrieval from memory is generally enhanced by duplicating the original stimulus and environmental conditions under which the information was committed to storage.

c. Capacity

The information handling capacity of the human operator is typically defined in terms of speed and accuracy of task performance or in terms of the maximum amount of information which can be processed per unit of time (these terms may be shown to be equivalent). By "information processed" is meant the number of equivalent binary decisions (bits) involved in the information processing.

Specific values for human processing capability are dependent upon many system- and use-determined factors. Since the human information processing is always specific to the conditions under which the measurements are obtained, it is only really meaningful to talk about the man-machine information channel rather than the human channel. For example, in situations where the input information varies along a single dimension (such as color, brightness, loudness, or pitch) and the task requires an absolute judgment about the stimulus in terms of this dimension, the human is capable of processing approximately 3 to 4 bits of information per stimulus event.+ That is, the

+ Absolute judgment refers to a categorization or identification of the signal or stimulus itself as opposed to a comparative judgment, in which the stimulus is evaluated relative, in some respect, to another stimulus.

human can only identify absolutely from 8 to 16 steps along any single sensory dimension. While some differences do exist between the human sensory channels in this respect, the processing is usually similar.

The addition of other dimensions (e.g., color, size, shape, brightness) to the stimulus will increase the processing ability of the man-machine channel in absolute judgment situations. However, the increase resulting from adding dimensions is at an apparently decreasing rate of change; the addition of a third dimension increases processing ability, but the amount of increase is less than that observed when the second dimension was added, and so on for further dimensional additions. However, it should be mentioned that, while the addition of stimulus dimensions appears to increase the total information processing capability of the human channel, the accuracy with which judgments are made decreases with respect to any particular dimension. Thus, the over-all result is one of an apparently fixed man-machine channel characteristic of 3 to 4 bits per stimulus or input event.

The channel capacity, or maximum information processing rate of a man-machine channel, appears to be directly related to human reaction time (see discussion on pg. 73, this volume). Measures taken in hundreds of experiments all indicate that simple reaction time to a single stimulus (in a "no choice" situation) is of the order of .12 to .25 seconds. Experiments on the time to react to one of several alternative stimuli (so-called "choice" or "complex" reaction time) increases as a logarithmic function of the number of possible stimuli closely approximated by the following formula:

$$\text{Complex Reaction Time} = K \log_2 (n+1)$$

where n is the number of equally likely alternative stimuli and K varies from 0.13 to 0.19 seconds. The term (n + 1) includes the ever-present additional alternative of reacting or not reacting. Thus, if simple reaction time represents the minimum time in which the binary judgment between stimulus presence or absence can be processed by man, then his maximum possible rate of information transmission, or capacity, is simply the inverse of his shortest simple reaction time, or about 8 bits per second.

Man-machine information handling capability is summarized in Fig. 2-11, which is a generalized plot of the results of several varied experiments. Fig. 2-11 indicates a fall-off at both high and low information presentation rates for a man-machine channel as compared to an ideal or perfect noiseless channel. Physically realizable equipment channels show an over-load fall-off at higher rates (the specific capacity depends entirely on the channel design) but not at the lower rates. This "vigilance decrement" (see this volume, pg. 66 et. seq., for discussion) appears to be characteristic only of man-machine channels.

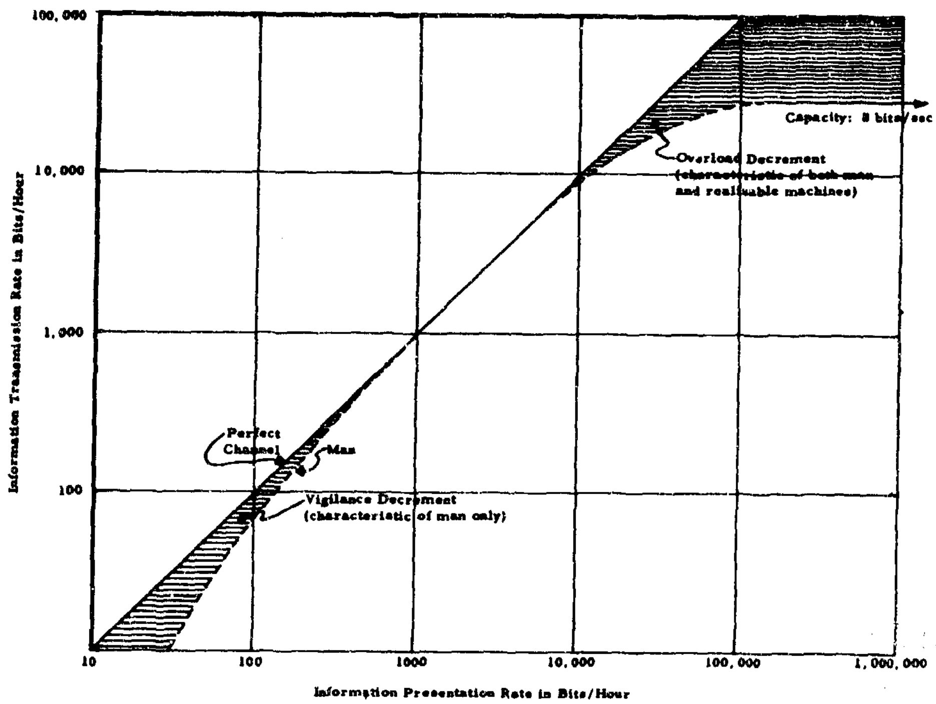

Fig. 2-11. Idealized graph showing man-machine channel capacity

Fig. 2-11 has been replotted in a different way to indicate the effect of information presentation rate upon errors produced by a man-machine channel. This is shown in Fig. 2-12. Although the two graphs are equivalent, Fig. 2-12 emphasizes the fact that there appears to be a broad optimum information presentation rate for minimizing errors in man-machine channels in the vicinity of 1/3 to 3 bits per second. The reader is invited to sort playing cards without error by color (1 bit per card) or suit (2 bits per card), being careful to subtract card handling time, and measure his own processing rate. He will find, as is usual in self-paced tasks of this nature, that his processing rate is within this range.

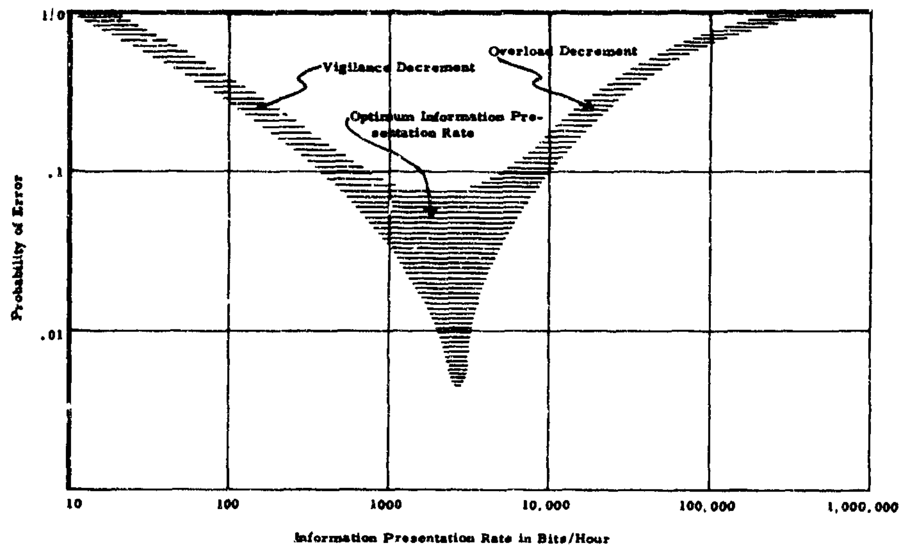

Fig. 2-12. Idealized graph showing error probability of a man-machine channel as a function of information presentation rate

d. Transfer Function

For continuous control tasks such as manual star tracking with the Type 11 periscope or manual control of submarine steering and diving, the nature of the information processing which personnel are called upon to perform is quite different than the processing functions previously described. In these and similar instances, the man is required to act as an element in a closed-loop control or "servo" system; as such, he must provide a dynamic input/output relationship which minimizes some measure of servo system error.

A typical system block diagram of such a servo system is shown in Fig. 2-13.

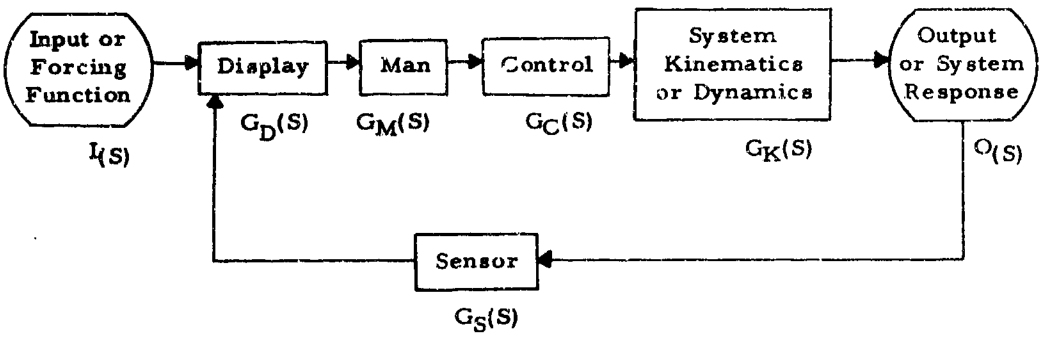

Fig. 2-13. A generalized closed-loop manual control system

In it, man acts as sensor, processor, and actuator; he receives signals from the display, transforms them in accordance with a transfer function into temporal force patterns, and manipulates a control in accordance with the generated force patterns.

Out of the last decade of work in this area there has emerged the realization that the human transfer function is largely determined by the dynamics of the forcing function and of the system which he is controlling. This dependency can be demonstrated quite easily. Using the symbols adjacent to the system

elements in Fig. 2-13 to represent the transfer functions in the complex frequency domain of each element, the actual closed-loop transfer function $G_{AL}(S)$ of the over-all system may be written as:

$$G_{AL}(S) = \left[\frac{G_D(S)\ G_M(S)\ G_C(S)\ G_K(S)}{1 - G_S(S)\ G_D(S)\ G_M(S)\ G_C(S)\ G_K(S)}\right]$$

Now let $G_{DL}(S)$ represent the desired closed-loop input/output relationship for the system. Then,

$$G_{DL}(S) = \frac{O(S)}{I(S)}$$

In order for the system to perform in accordance with the foregoing mathematical statement, the man's processing characteristics (i. e., transfer function) must approximate the following form:

$$G_M(S) = \frac{G_{DL}(S)}{[1 + G_{DL}(S)]\ G_S(S)\ G_D(S)\ G_C(S)\ G_K(S)}$$

This clearly shows that the man must compensate for the display, control, and system dynamics in a rather direct way.

The results of many studies of human behavior in continuous control systems of this nature point towards a generalized transfer function for the "human servo element" of the following form:

$$G_M(S) = \frac{Ke^{-Ts}\ (1 + T_L S)}{(1 + T_N S)\ (1 + T_I(S))}$$

where

$G_M(S)$ = human transfer function

K = ratio of output position signal to input position signal

T = time lag between signal occurrence and initial response (0.2 to 0.5 seconds)

T_N = neuro-muscular time lag (0.1 to 0.16 seconds)

T_L = lead time constant (0.25 to 2.5 seconds)

T_I = lag time constant (5.0 to 20 seconds)

S = complex frequency argument

Based upon empirical results, Fogel[7] has suggested that a manual closed-loop vehicular control system should have the characteristics shown in Fig. 2-14. in order to make best use of the man in a servo element.

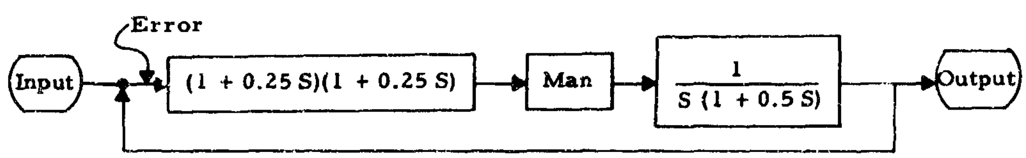

Fig. 2-14. Vehicular system dynamics recommended by Fogel, based on survey of experimental studies and related data

Birmingham and Taylor[2] have stated that system dynamics in any kind of manual control system should be so designed as to require that the man act as a simple low pass amplifier with a corner frequency at about 3 radians/sec. A more detailed discussion of man as a servo element may be found in these two excellent references.

e. Feedback, or Knowledge of Results

Analysis of human data processing activies reveals few if any open-loop activities, i.e., activities wherein some feedback of what happened or what is about to happen is not available to the human in some form. In fact, it appears that any activity of which a human is a part either as an initiator of events or as a link in a series of events is in essence a closed-loop system. The performance of personnel can be optimized by providing them with proper feedback of information about themselves and their performance. Information concerning the correctness of his action enables the human, as a self-correcting

system element, to refine his action(s) and correct further. By social habit, the human operator seeks confirmation of his self-concept in every action and, inasmuch as his reactions to specific system-related stimuli are intrinsically bound up with his emotions and intellectual functioning, the whole man is affected by the need for information feedback. Thus, feedback becomes an intrinsic requirement for human information processing. This feedback is not limited to results of actions already carried out; it may also include anticipatory feedback or prediction of future events. It is not at all surprising then that the need for adequate and timely information presentation is acute in most man-machine functions.

The over-all adequacy of feedback information can be judged by its content and timeliness. Content considerations in any particular situation largely involve the relevancy and amount of information presented to the human as well as the sensory mode through which the information is channelled. The more precise the information required, the more the need for precisely relevant and substantive feedback information. Timeliness considerations involve the temporal relationships among the amount of information available, the time which the operator has to utilize it, and the speed with which the operator can acquire it and put it to use.

2.3 Actuating

Thus far, we have considered the comparative aspects of personnel and equipment with regard to sensing and processing of information. It is evident that apparatus can be supplied to augment man's sensing and processing capabilities and that man can augment strictly equipment capabilities. In this section, the actuating or control function will be considered, together with comparative man and machine capabilities to control, modify, manipulate, move around in, and otherwise affect his environment. Again, the system designer can extend the effectiveness of both man and machine by careful application of available information about their relative advantages and limitations. The terms of reference are presented below, followed by guidelines for assignment of actuating functions to man and machine.

Personnel and equipment differ in the overtness of actuating performances. The concept of actuation, when applied to personnel and equipment thus may not always have the same meaning. Actuation generally connotes overt or observable movement. Most machine reactions to stimuli are overt, e.g., mechanical, electrical, etc., and can easily be classified as actuations. Human

reactions to impinging signals, however, are not always observable and, in some instances, are not even easily measurable (e.g., an emotional response to some stimulus pattern or, again, the intellective grasping of stimulus relationships as in a thought process). Personnel are capable, then, of non-observable actuating responses to impinging stimuli. It is important to recognize that a man can, upon appropriate signals, place into action a chain of varied events which can occur entirely within himself and which are extremely hard to make explicit.

Man's verbal response capacities also set him off as distinct from and vastly more flexible (for most circumstances) than his equipment. Indeed, the ability to make meaningful verbal responses makes man unique among existing animals and machines. The ability to respond through varied language media enables personnel to communicate not only with their equipment, but also -- and primarily -- with other personnel.

Personnel and equipment exhibit similar motor performance characteristics. The concept of actuation also is inextricably related to motor performance (or movement), both for personnel and for equipment. Three types of movement can be identified for both the human and comparable actuating equipment:

- Isometric or "static" movements are those wherein the prime task of the actuating mechanism is to maintain its position. Little actual movement is accomplished, but work energy is expended to maintain the desired position.

- Positioning movements, whether momentary, repetitive, or continuous, generally involve the actuation of a structural member first in the desired spatial direction and secondarily to the specified spatial locus. For example, actuating a crane involves a gross positioning and directing of the apparatus and then the finer movement of the equipment extremities. In the discussion of human positioning movements, we commonly refer to reaction time (time to begin or to complete (depending on the situation) an overt action) as the important measure.

- Adjustive or continuous action is a third type of actuation usually involving close-tolerance positional and rate movements. Adjustive movements normally occur in a continuous reaction task wherein the information available in a closed-loop system is changing. Personnel as well as equipment exhibit closed-loop servo performance characteristics. Each can respond with a predictable characteristic -- or nearly so -- to indicate positional and rate changes in a dynamic information control system. In discussions of human adjustive behavior we commonly refer to timing as the appropriate time dimension of the response.

Assignment Guidelines

Personnel and equipment both exhibit measurable actuating characteristics as long as the actuation response is overt. Work energy is usually expended in the actuation response -- that is, a force is distributed in both time and space. Function allocations to personnel and/or equipment must take into account at least these four measurable characteristics of actuating responses:

. Speed of actuation.

. Accuracy and precision of performance.

. Force and strength of response.

. Reliability of performance.

The factors listed above may appear in any type of actuation.

2.3.1 * Where speed, accuracy, and/or reliability of actuation is critical, equipment should perform the actuating tasks.

Personnel usually <u>cannot</u>:

a. Act as fast as comparable actuating mechanisms.

b. Exert as much force as comparable actuating mechanisms.

c. Act as reliably in a completely defined actuation function.

d. Perform reliably in as wide a range of incompatible or inclement environments as selected comparable equipment.

e. Actuate many things at once (parallel operation).

2.3.2 * Where complex actuations requiring flexibility, adaptability, and coordination are required, personnel should perform the actuating tasks.

Personnel usually <u>can</u>:

a. Learn complex actuation principles and relationships.

b. Exhibit variety in the repertoire of possible actuation methods and principles.

c. Develop highly refined and coordinated motor movements.

d. Combine, in one unit, a continuously operating adaptable closed-loop control mechanism with wide capacities for resolving time-dependent problems (e. g., involving prediction, the utilization of stored experience, etc.).

e. Combine sensor, processor, and actuator functions.

2.3.3 * When personnel must perform actuating tasks, human actuating characteristics must be taken into account in system design.

Most human actuating characteristics are directly relevant to equipment and component design and have, therefore, been included in appropriate parts of Volume 2, "Design of Equipment." Attention is especially directed to the following parts of Volume 2:

- Pp. 113-115 for a discussion of operator strength and force capacity.

- Pp. 123-145 for specific design requirements for hand controls as related to human actuating characteristics.

- Pp. 147-154 for specific design requirements for verbal communications equipment as related to human speech characteristics.

- Pp. 159-184 and 210-215 for specific design requirements for panels, consoles, and seats as related to dimensional characteristics of the human body.

- Pp. 276-277 and 282-285 for specific design requirements for improving maintainability as related to human body dimensions and weight-lifting capability.

3 Evaluation of Task Assignments

It is important to recognize that there are always alternatives to a particular system design and that, once a particular system concept has been selected for further study or development, there will be alternative ways of mechanizing it. This section is concerned with evaluation of alternative mechanizations from a man-machine standpoint. Only general advice can be given in this area, since the bases for and methods of evaluation will differ in every instance.

3.1 Criteria

The basis for comparison of two alternatives is called a criterion or a set of criteria. Following is a list of some of the more important criteria observed in human factors work on the FBM system:

Speed or its inverse, performance time (mean and variability)

Accuracy (deviation) and precision (variability)

Error probability

Dependability (maintainability and reliability)

Adaptability (of system to changes in requirements, equipment design, or operating conditions)

Mobility (e. g., of test equipment)

Complexity

Graceful degradation (ability to continue to operate although at substandard levels of performance)

Weight

Space

Feasibility (hardware state of the art or human limitations)

Personal involvement (extent to which personnel identify themselves with their tasks or are aware of system operation)

Personnel quantity and quality

Personnel hazard and risk of equipment damage

Tactical delivery schedule (time for system to become operational)

Equipment weight and/or volume

Training costs (personnel, time, facilities)

Manning level (includes shift weighting factor)

Development cost (including programming)

Logistics costs and policy (pipeline and spares provisioning policies)

Equipment unit cost in production (including spares)

System environment (ability to operate under various climatic, terrain, socio/psychological, political, and other conditions)

3.2 Evaluation Schemes

Theoretically, each system operating or maintenance task may be assigned some "effectiveness" numbers which represent the suitability of different man-machine "mixes" in getting the task done. Given a reliable matrix of these numbers, a planner could try out various approaches to an optimum allocation of tasks to man and machine.

An effectiveness number must be related in a definite way to the criteria which prevail in the real situation; some means must exist for "mapping" values back and forth from the criterion dimensions to the effectiveness scale. In the preceding paragraph we have mentioned some of the criteria which apply to the common classes of system tasks. How is one to "map" these dimensions, let alone combine them?

A start can be made by recognizing that some criteria which are physically continuous (or otherwise inconvenient) can be handled in terms of a limited number of discrete levels. Thus a weight criterion for an FBM checkout device might have only three values for practical purposes because these three represented the major model possibilities foreseen by the technology. These values might be 61 pounds for a minimum built-in test panel, 108 pounds for a more inclusive array of test indicators, and 220 pounds for an elaborate switching center. Similarly, "ease of interpretation" levels could be defined and the possible "candidates" might be few indeed.

With about half a dozen major criteria and only a few levels on each dimension, the possibility exists of deriving paired-preference values across the different criteria. A military authority or technological expert might, for example, be willing to choose which of two discrete "situations" would be most advantageous to a given weapon system mission. The situations would be contrived to pit one criterion against another in a systematic fashion, though as far as the judge is concerned, he is simply making a choice from among two alternatives at a time.

The statistical treatment of such data would depend on the qualifications of the judges, their confidence and unanimity in assignment, and the assumptions that one is willing to make about the utility function being sought. If a set of alternatives can be reliably ranked, and if a "difference order"+ exists in these rankings, then utility numbers can be obtained with surprisingly few additional

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+ In a supply framework, a logistics planner might assert that he would rather replace X with Y than replace A with B. "Replace X with Y" is a difference, and the preference relation between such differences is a difference order.

assumptions. The meaningfulness of the numbers is still controversial and must be determined by applying them over a wide range of circumstances. Nevertheless, such methods deserve study and application.

To implement such an approach, the following steps would be involved:

. Select a mission phase and subsystem.

. List the major criteria that will apply to the situation.

. Formulate via heuristic methods the major feasible subsystem configurations for the situation, if possible reflecting the principal criteria by discrete equipment and man-machine role differences.

. Arrange the feasible criterion levels systematically into pairs. +

. Obtain rankings of criterion combinations and difference-order data if possible.

. Derive utility numbers for each criterion.

The above procedure serves to emphasize, via the utility measure, which criteria deserve the most attention from the man-machine task-designation standpoint. It might happen, for instance, that the criteria which come out with the highest utility values are not particularly sensitive to man-machine "ability" differences, in which case subsidiary values such as cost or convenience could decide the final configuration. For those cases where the criteria with high utilities do have the possibility of being instrumented by either manual or automatic method, the planner will probably have to refer back to the unique capabilities of the human and the device and to perform some more or less systematic weighting of alternatives. The "suitability" of man or machine for the different criteria is naturally complicated, but some rough guides can be stated for a start. In Table 2-9, for instance, the numbers indicate the general advisability of assigning tasks according to the criteria. Thus, the man gets a high "grade" of three on flexibility, a low grade on speed, and so forth. In the same way, the machine is high on speed, etc. These numerical values were arbitrarily assigned and may be modified drastically for a given subsystem configuration. A complete discussion of this type of evaluation scheme may be found in Wohl and Swain (24) and in Teeple (21).

+ Triads, partial pairing, and other grouping techniques might be employed for convenience in the data collection.

Table 2-9
Illustration of Criterion Weighting

Criterion Unit	Suitability for Man	Suitability for Machine
Speed		3
Accuracy		2
Reliability		2
Adaptability	3	
Personal Motivation	2	
Personnel Hazard		2
Time for System to Become Operational	2	
Equipment Weight	1	
Equipment Space	1	
Training Costs		2
Manning Level		2
Logistics Costs	2	
Equipment Costs	2	

Another type of task assignment evaluation technique, reported by Kurke[10], is of particular importance here because of its direct association with the Operational Sequence Diagram. (See previous discussion on pg. 50, et. seq.) To illustrate the use of OSD's in evaluating man-machine task assignments, Kurke employed a hypothetical system example shown in Fig. 2-15 A, in which Act A results in a series of operations to elicit Act K. Symbols B and C represent alternate environmental conditions which are necessary for or inhibit this process, respectively. B conditions occur 90% of the time. Upon receipt of indications D and E, the operator decides (G) upon Action H rather than J. H interacts with Condition B to produce Act K. Should the decision G to activate H be made under environmental Condition C, Error L will result. Using the notation described on pages 57 and 58 of this Volume, the system under normal operating conditions may be described as:

$$(A_i \longrightarrow D_i) \cdot (B_b \longrightarrow E_i) \longrightarrow (G_a \longrightarrow H_a \longrightarrow \overline{K}) + (G_b \longrightarrow J_i) \qquad (1)$$

$$B_a \cdot H_a \longrightarrow K_i \qquad (2)$$

Analysis of the diagram shows that the sources of "human error" are centered about the decision element G. The operator may respond incorrectly or fail to respond at all to various combinations of signals. In reference to decison G, the errors may be divided into input and output error, S and R, and described as:

$$S_i \longrightarrow (D_o \cdot E_i \longrightarrow G_i) + (D_o \cdot F_i \longrightarrow G_i) + (D_i \cdot E_i \longrightarrow G_o) + (D_i \cdot F_i \longrightarrow G_a \longrightarrow H_b \longrightarrow \overline{L}) \tag{3}$$

and

$$R_i \longrightarrow G_i \longrightarrow (H_o \cdot J_o) + (H_o \cdot J_i) \tag{4}$$

The human error can be reduced by two means. One method is by introduction of a "logic switch" to replace the human decision-making function (Fig. 2-15 B). This will provide an automated system where

$$D_i \cdot (E_i \cdot F_o) \longrightarrow M_i \longrightarrow H_i \longrightarrow \overline{K} \tag{5}$$

The other method would be the inclusion of additional components to permit the system to operate under Condition C as well as B. The inclusion of component N would change the logic of the system to:

$$(A_i \longrightarrow D_i) \cdot (B_b + C_a) \longrightarrow [G_a \longrightarrow (H_a \longrightarrow \overline{K}) \cdot (H_b \longrightarrow \overline{N})] + (G_b \longrightarrow J_i) \tag{6}$$

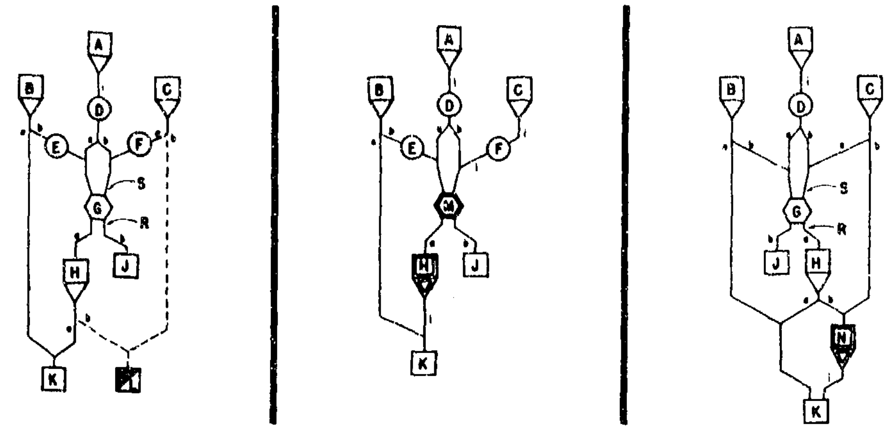
$$C_b \cdot H_b \longrightarrow N_i \longrightarrow \overline{K} \tag{7}$$

$$(B_a \cdot H_a) + (H_b \longrightarrow N_i) \longrightarrow K_i \tag{8}$$

as shown in Fig. 2-15 C. This arrangement would eliminate the need to discriminate between E and F. The nature of the input error source then becomes

$$S' \longrightarrow [D_o \cdot (B_b + C_a)] + (D_i \cdot B_o \cdot C_o) \longrightarrow G_i \tag{9}$$

while R remains unchanged from Equation (4), above.



A. ORIGINAL SYSTEM B. AUTOMATIZED VERSION C. MANUAL MODIFICATION

Fig. 2-15. System comparisons

The solution of the problem requires some quantitative information such as the reliability of components. For illustrative purposes, let us assume the reliability of the original system which equals (abcdef) = 0.768, where

a	= Reliability of Sequence ($A_i \longrightarrow D_i$)	= 0.99
b	= Ratio of B:B and C	= 0.90
c	= 1 - P(S)	= 0.95
d	= 1 - P(R)	= 0.95
e	= Reliability of Sequence ($B_a \longrightarrow \bar{K}$)	= 0.99
f	= Reliability of Sequence ($G_i \longrightarrow \bar{K}$)	= 0.99

and P(S) and P(R) are the probability of human error at S and R respectively.

The first alternative of automating the system would replace human decision G with a logic switch M, thereby eliminating S and R. Assuming that the reliability of the logic switch is 0.99, this improvement would increase system reliability to 0.864.

The second alternative, that of providing an additional component (with very poor reliability) to reduce the human error potential would yield a reliability of (abcdef) + (adhjkmn) = 0.858 + 0.046 = 0.904, where

h	=	1 - P(S')	=	0.99
j	=	C:B and C	=	0.10
k	=	Reliability of Sequence ($G_a \longrightarrow H_b \longrightarrow \overline{N}$)	=	0.99
m	=	Reliability of Sequence ($C_b \longrightarrow \overline{N}$)	=	0.99
n	=	Reliability of Sequence ($H_b \cdot C_b \longrightarrow N_i \longrightarrow \overline{K}$)	=	0.50

Collecting the analyzed data for various combinations of degree of automation and component reliabilities as on Fig. 2-16 should yield data to establish the trade-off point when determining the allocation of man-machine functions in developing a system.

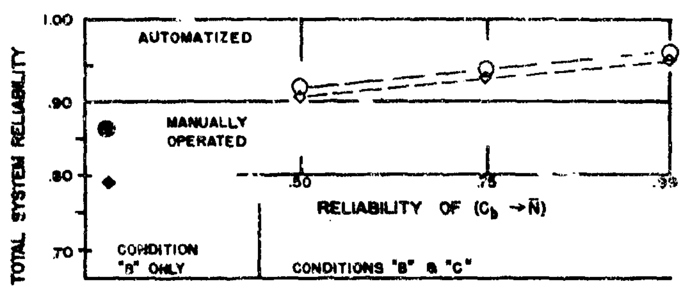


Fig. 2-16. System reliability

This particular analysis of system reliability leads to the conclusion that automating the existing system is considerably less effective than developing a new manual system with the capability of operating under a greater variety of environmental conditions. Some little additional improvement in system reliability can be obtained by automating the latter system. The data in Fig. 2-16, together with additional economic and engineering considerations, should be among the factors which determine how best to improve the system (i. e., whether to automate, to increase the scope of the system, to improve reliability of sequence ($C_b \longrightarrow \overline{N}$), or some combination of these approaches).

4 Man-Machine Interface Requirements

Once a final evaluation and selection from among alternative system and/or subsystem mechanizations has been made, the next step in the system design process is to prepare subsystem design requirements or specifications. Specifying the man-machine interface requirements at this stage is largely a matter of listing the specific information items to be transferred between man and machine during the various phases of system operation. If an operational sequence diagram has been prepared, this step is vastly simplified.

Two general areas of man-machine interface requirement may be distinguished:

- The operating interface.
- The maintenance interface.

Information transfer requirements for the two areas differ mainly in terms of the task differences. Guidelines for selection and/or design interface elements in both areas have been developed and are presented in detail in Volume 2, Section 3, "Design of Equipment for Operation," and Section 4, "Design of Equipment for Maintenance." The discussions in Volume 2 provide information concerning the medium and the specific method of information transfer, the relative utility of various kinds of display and control components, and their arrangement on panels and consoles.

The intelligent application of human factors considerations in systems engineering requires, in effect, a broad state-of-the-art knowledge of human capabilities and limitations with respect to physical, physiological, psychological, and psychophysiological requirements imposed by mission, system- and use-determined factors. The final specification of a man-machine interface must reflect these factors as well as the man-machine factors themselves. It is to the understanding of the total process in which human factors is imbedded that Volume 1 has been dedicated.

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